FATIGUE MONITORING OF 70-30 COPPER-NICKEL

Franklin Bruce Lash

United States
Naval Postgraduate School

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Lieutenant Commander, United States Navy
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ABSTRACT

Recent tests by G. L. Rowe indicated the possibility of monitoring fatigue damage of 70-30 copper-nickel by use of a commercial fatigue life gage. The work reported herein, however, which includes tests at cyclic strain levels considerably higher and lower than those used by Rowe, suggests that much more study and development will be required before in-service monitoring will be useful or reliable. Fatigue failure, using initial surface crack formation as a criterion, takes place at low cyclic strain levels with appreciably smaller gage indication than does failure at medium or high cyclic strain levels. It is further noted that ability to detect surface cracks depends greatly upon the expertise of the observer so that a less subjective criterion of failure should be developed.

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SYMBOLS AND DEFINITIONS

cpm	Cycles per minute
in.	Inches
^{0}F	Degrees Fahrenheit
KSI	1000 pounds per square inch
N	Number of cycles
PSI	Pounds per square inch
ΔR	Resistance change
ε	Strain, 10^{-6} inches per inch
ε_c	Compressive strain indication
ε_n	Strain reading in neutral position
ε_R	Cyclic strain amplitude, also called strain level $\frac{1}{2}(\varepsilon_t - \varepsilon_c)$
ε_t	Tensile strain indication
μ	Micro (10^{-6})
Ω	Ohms

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Mr. R. J. Whitehead of Micro-Measurements, Inc., Romulus, Michigan, who provided the gages for this study;

LT G. L. Rowe, USCG, who initiated this study and provided much of the basic information;

Mr. H. G. MacKerrow of San Francisco Bay Naval Shipyard, Vallejo, California who provided the chemical and physical analyses of the material.

I. INTRODUCTION

70-30 Copper-Nickel is a tough alloy designed to withstand high stresses over a wide range of temperatures and in severely corrosive environments. Because of these properties the alloy has been accepted for wide use in marine construction. It has been the predominant material used in the main sea water piping systems of Navy, Coast Guard, and Merchant Marine vessels. These systems are subject to varying and continual strains. The failure of any system could be critical, especially in a deep diving submersible.

The ability to signal when fatigue failure is about to occur in a material has long been of interest. To date no satisfactory method of prediction has been developed. A new device called the S/N* Fatigue Life Gage was invented by Mr. Darrell R. Harting of the Boeing Company, Seattle, Washington. This gage, described in Appendix A, is used to aid in predicting failure. This is accomplished by observing the change in the electrical resistance of the gage. The resistance change is caused by the straining of the gage material which follows the straining of the material to which the gage is bonded. By conducting a series of tests with these gages on various materials it has been found that under certain circumstances the failure of a material can be predicted by monitoring the resistance change of the gage. Different values of these resistance changes have been found

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*Trademark: Micro-Measurements, Inc., Romulus, Michigan

for various base materials. Typical values of resistance change at failure have been between four and eight ohms for the 100 ohm sensor (Ref. 3).

Knowing that these gages have shown good results for several other materials it was decided to investigate the suitability of this gage for use with 70-30 copper-nickel.

The study was begun last year at the Naval Postgraduate School by G. L. Rowe (Ref. 4). The immediate goal of his work was to obtain sufficient data to relate the change in gage resistance to crack initiation in the cyclically strained base metal specimen to which it was applied. It was known that the gage had limitations in the low strain levels when applied to other materials (Ref. 3). However, it was believed that due to the similarity of the constantan grid material (approximately 55% copper, 45% nickel) and the 70-30 copper-nickel specimen material that the gage could be correlated over all ranges of strain.

The results obtained by Rowe were generally favorable, indicating that there was reason to continue the study. Therefore, the present work was undertaken to:

1. Independently verify Rowe's findings for medium cyclic strain levels;
2. Obtain data for cyclic strain levels lower and higher than those investigated by Rowe;
3. Observe the effects of aging;
4. Obtain block cycling data;
5. Compare the observed results of the tests with the characteristic curves provided by the manufacturer;

6. Make recommendations as to further investigation to be accomplished prior to actual field application of the gage to copper-nickel piping in actual service.

The aging tests were intended to determine the effect of a rest period on the resistance of the gage. Any significant decrease in the resistance of the gage while the specimen was not being strained would complicate the interpretation of gage readings. Block cycling was to be done to assess the results of applying various random loads to the gage. It was hoped that the resistance change would be constant at crack initiation regardless of the load history.

Initial tests in this study verified the results obtained by Rowe. However, at low strain levels it was observed that the resistance change at crack initiation was much lower than was anticipated. During these tests a question as to the suitability of the fatigue specimen being used was raised. The initial tests were conducted using the S/N fatigue specimen designed by Mr. W. T. Bean. (We will refer to this specimen as Type 1) (Figure 1). These tests were numbers 1A through 5A inclusive and 1 through 7. Tests number 8 through 11 were performed on a specimen of the same configuration (Type 1) but lengthened to ten inches. This was done to allow testing at lower strain levels. The cracks in specimen Type 1 at the low strain levels initiated on the bottom surface and propagated upward. These cracks started at the juncture of the curved and flat section. It was decided that these results

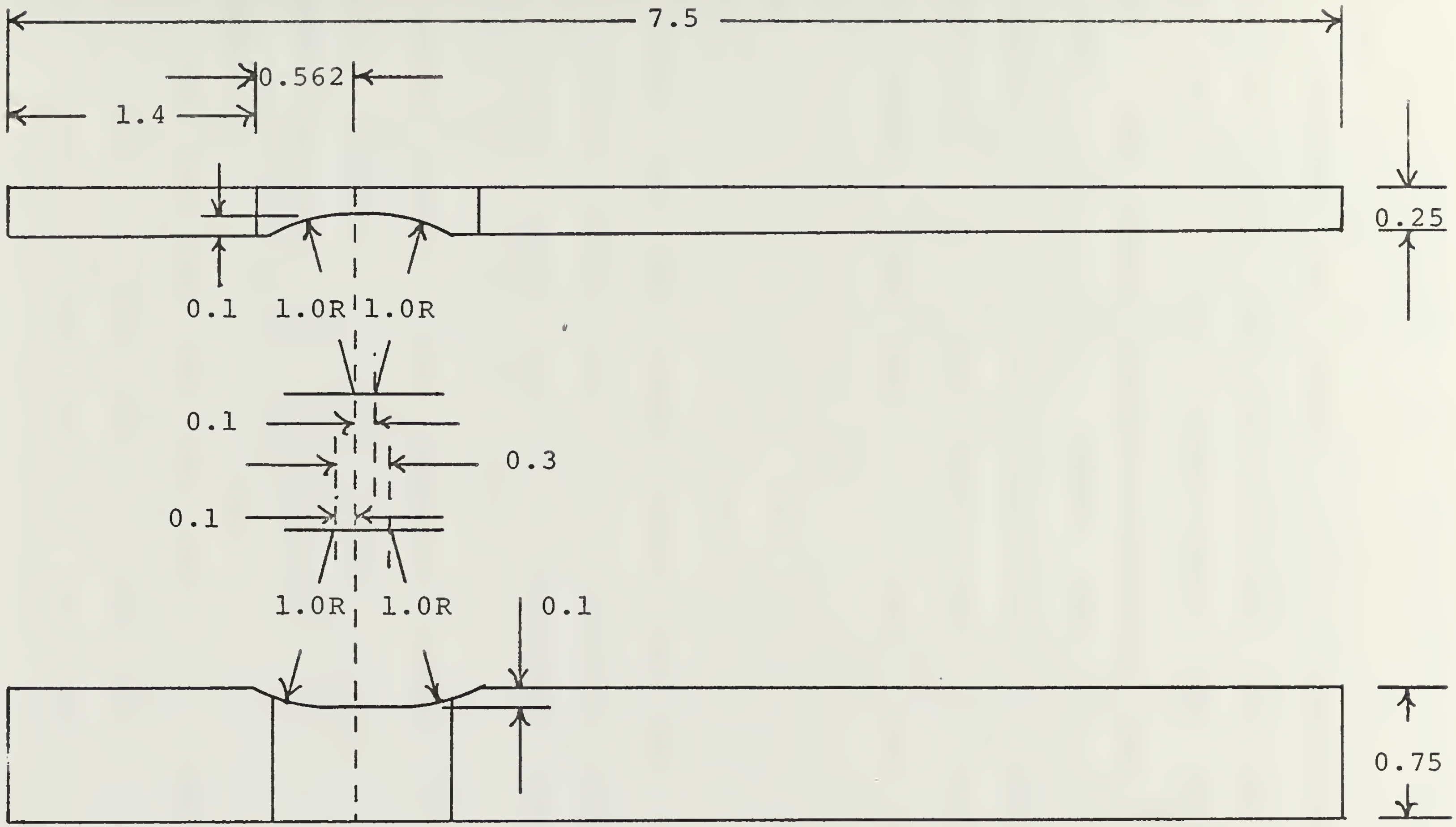

Figure 1. S/N Fatigue Specimen, Type 1

were due to the existence of a stress raiser on the bottom surface at those points.

To eliminate this tendency to crack on the bottom surface, a series of modified specimens was tested. Specimen types 2 and 3 (Fig. 2 and Fig. 3) were tested. Type 2 had the stress raiser on the bottom eliminated completely, only the width of the specimen being reduced. However, the reduction in area was insufficient to make this reduced area the point of maximum strain. As a result the specimen cracked at the edge of the clamping block (Fig. 4). It was felt that any further increase in the depth of the side cuts would create excessive stress raisers in these areas. To avoid that possibility, specimen type 3 was tested. A stress raiser still exists on the bottom. The effect of this stress raiser did not appear to be sufficient to make the bottom surface the preferred area to crack. Further tests at various strain levels appear to have verified this belief.

As the number of tests completed increased, it was noted that the resistance change at the time cracks were first detected decreased. This was attributed to the fact that the experience level of the investigator was increasing. To try to determine when the cracks were initiating, a 500x microscope was used. The surfaces of the specimens were inspected at various periods during the test. In so doing it was possible to verify the existence of small cracks very early in the life of the specimen. As the test progressed these

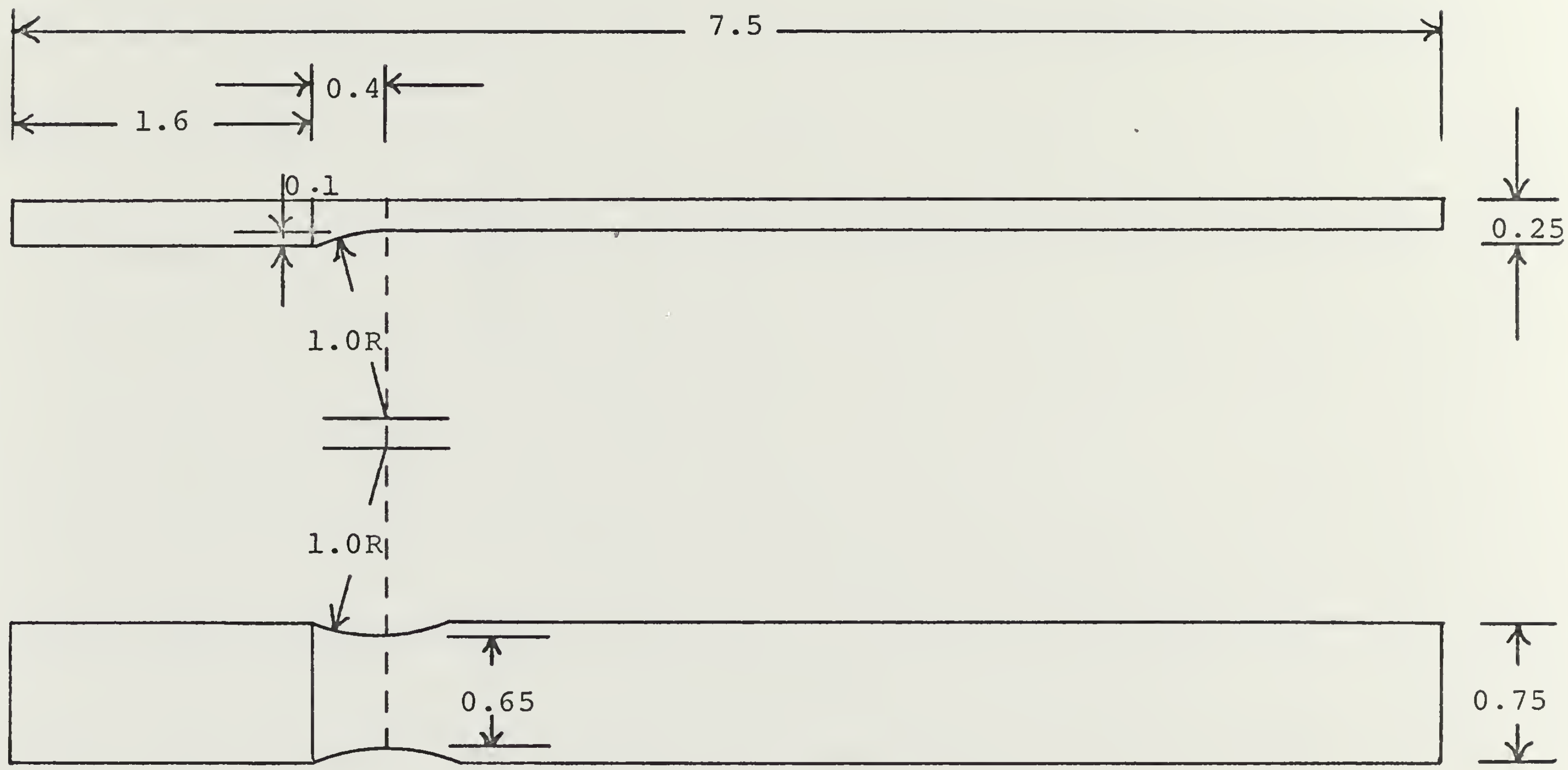

Figure 2. S/N Fatigue Specimen, Type 2

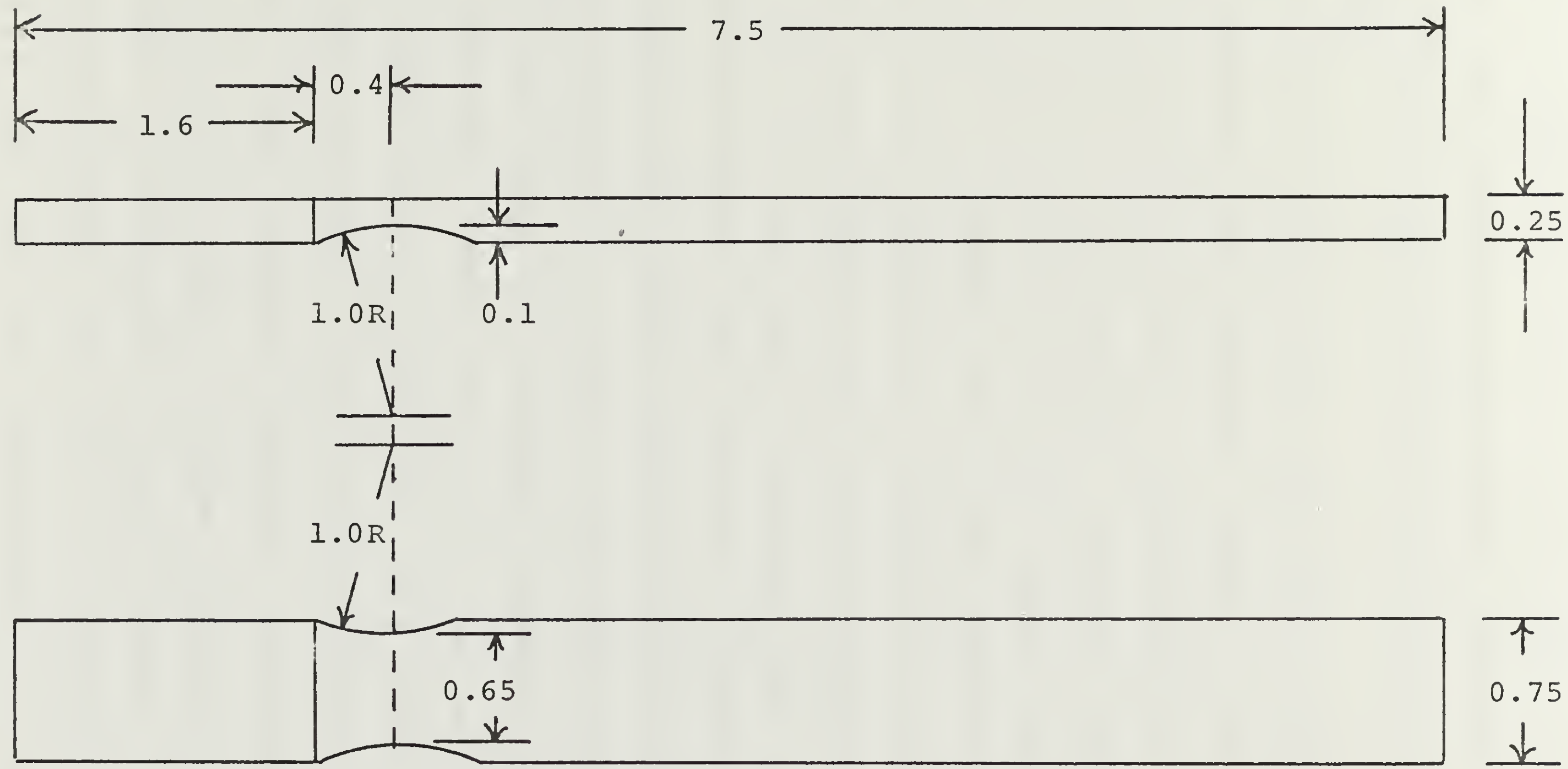

Figure 3. S/N Fatigue Specimen, Type 3

cracks became observable over the entire width of the specimen except under the gage and various cracks propagated deeper into the material. This ultimately led to gross failure of the specimen.

The ability to detect these early cracks is dependent upon the expertise of the observer. Because of this it is now felt that possibly the use of "crack initiation" as a failure criterion is too subjective. Also the fact that the initial cracks were observed when a major portion of the material life of the specimen was not yet expended seemed to indicate that crack initiation as a failure criterion is not sufficiently closely keyed to the practical employment of the material. In other words, early detection of hairline cracks is not adequately keyed to the necessity of removing an operating copper-nickel piping system from actual service and repairing or replacing it. Based on these observations it was decided that additional tests should be conducted using failure of the gage or total specimen fracture as a failure criterion. Tests conducted using this basis for failure show that the resistance change at gage failure depends on the strain level at which tests are conducted. Knowing this, it is felt the use of the gage in a system subjected to various unknown levels of strain would not provide useful information. As a result block cycling tests were not conducted.

It may be hoped that the manufacturers of the gage will be able to overcome the difficulties mentioned above, inasmuch

as the idea still seems to have much promise. However, we conclude that it would not presently be justified to consider employing this device for in-service monitoring of copper-nickel piping.

II. EXPERIMENTAL PROCEDURES

To accomplish the objectives of this study a series of tests was conducted. Each test was assigned a test number. A description of the apparatus used can be found in Appendix C. A tabulation of the rough data for all tests is found in Appendix D.

The general procedures for all tests were indentical. The bending specimen was prepared as outlined in Appendix B. The clamping block was positioned to obtain the desired strain. The specimen was placed in the clamping block. The exact positioning of the specimen depended on the specimen configuration. For specimen type 1 the vertical edge of the longest reduced section was aligned with the edge of the clamping block (Fig. 1, Ref. 4). For specimen types 2 and 3 the end of the specimen was aligned with the end of the clamping block (Fig. 4). In all cases the horizontal edge of the specimen was aligned with the edge of the clamping block. A specimen compensating block was used to ensure a balanced clamping pressure. Since all of the tests conducted in this study were in reversed bending, the shim plate was positioned on top of the specimen. By placing the shim plate in this position the specimen was cycled through both tension and compression.

With the specimen properly mounted in the clamping block the gage leads were connected. The gage was connected to a terminal strip mounted on top of the clamping block. This method of connection was used to avoid any interference between the electrical leads and the flywheel at high strain

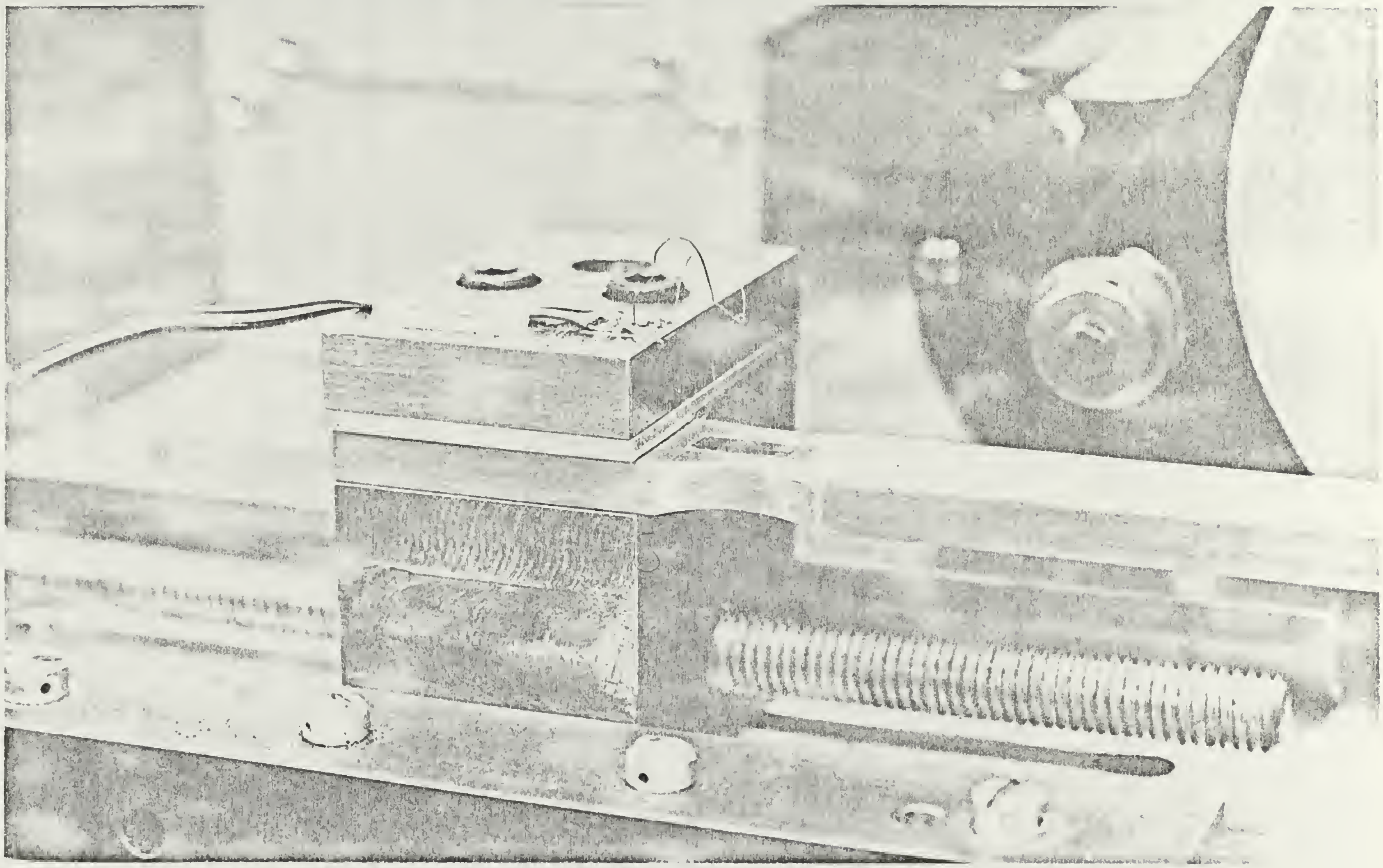

Figure 4. Test Specimen Mounted in Clamping Block

levels. A one inch piece of 134-AWP solid copper wire was used to increase the length of the gage leads. This was done to avoid contact between the leads and the clamping block. It also helped to eliminate the possibility of gage lead fatigue. Figure 4 is a photograph of the completed installation.

After the gage was connected, the specimen was ready to be tested. The loading spring was installed. The spring is located directly under the flywheel of the machine. It is inserted through a hole in the base of the testing machine and is held in place by the spring retainer pin. With the spring cap installed, the specimen is kept in continual contact with the eccentric. The temperature was then recorded. For all tests this varied between 73° to 76° F. The initial resistance was then recorded. To obtain the initial resistance, the flywheel is placed in the neutral position. This was done by positioning the arrow on the cam in a horizontal position. It was maintained in this position by inserting an allen wrench through a hole in the positioner block into a hole in the cylindrical surface of the flywheel. This position was the reference position for all resistance readings (Fig. 9).

After the initial resistance reading was taken, the S/N resistance meter was disconnected. Using the S/N Fatigue Gage in one leg of a half wheatstone bridge and a decade resistance box in the other leg, a BUDD/STRAINSERT Strain

Indicator was connected. The strain indication in the neutral position was recorded. The allen wrench was then removed. The flywheel was put into the position of maximum compression and the strain level was recorded. The flywheel was then cycled into the position of maximum tension and the strain level was recorded. The flywheel was then returned to the neutral position and the allen wrench inserted in the positioner block. The strain indicator was disconnected. The resistance meter was connected and the resistance was recorded. The resistance meter was then disconnected and the strain indicator was connected. The strain in the neutral, maximum compression, and maximum tension positions was recorded.

The specimen was then hand cycled through ten cycles. During cycles six through ten, the strains in the neutral, maximum compression, and maximum tension positions were recorded. After the initial ten cycles the flywheel was returned to the neutral position. The strain indicator was disconnected. The resistance meter was connected and the resistance recorded. For the remainder of the test the resistance meter stayed connected.

The average strain level for cycles six through ten was used as the strain level characterizing the test. The strains obtained in cycle ten were used to calculate what has been called mean strain in this thesis (see Appendix E). The resistance after ten cycles was used as the reference for computing ΔR. This procedure for computing ΔR minimizes the effects of plastic flow and of "seating" of the specimen (Ref. 3).

The specimen was hand cycled through 100 cycles and the resistance recorded. At this point in the test hand cycling was terminated. The test was continued using the variable speed motor. The tests were conducted at a cyclic speed of 1800 cpm. At the desired number of cycles the motor was stopped. The flywheel was put in the neutral position and the resistance was recorded. The ΔR was computed. The value of ΔR vs. N was plotted to compare with the characteristic curves. Section III includes plots of some of the tests which were conducted.

The initial objective of this study was to correlate the resistance change of the gage to crack initiation. The cracks were located by applying a coat of W. T. Bean "Solder Stop" and visually inspecting. The Solder Stop is a surface coating that accentuates the cracks by a shadowing effect. A desk type flourescent lamp was used to provide direct lighting on the surface of the specimen. An 8x eyepiece was used to examine the surface. A discernable crack in the material would show up as a fine black line. Reference 4 indicates initial cracking will occur at about 4.5 ohms. Initial tests appeared to verify these results.

The results at low strain levels (i.e., strain amplitude, ε_R) deviated from the expected results. During test number eight, conducted at $1364\mu\varepsilon$, cracking of the specimen occurred with a resistance change of less than 1.5 ohms. The cracking initiated on the bottom surface and penetrated upward through

the specimen. After 500,000 cycles, with a ΔR of 0.80 ohms, no cracks had been detected. At 600,000 cycles a ΔR of 1.44 ohms was recorded. A plot of the data showed a large increase in the slope of ΔR vs. N. A visual inspection failed to indicate any cracks on the upper surface. However, the lower surface had a crack that had propagated half way through the specimen. Test number nine conducted at a strain level of 1381$\mu\varepsilon$ verified these results. However, in this case after 325,000 cycles, with a ΔR of 0.80 ohms, initial cracks on the upper surface were detected. At 547,750 cycles cracking initiated on the bottom surface. This crack propagated upward and at 560,000 cycles the slope of ΔR vs. N increased.

At this time it was determined that the original specimen, type 1, had a stress raiser that made the lower surface the preferred area to crack. To eliminate this as much as possible, specimen type 3 was used for following tests.

Knowing that cracking had occurred so early in some of the preceding tests, all specimens were thoroughly inspected every time a resistance reading was taken. This resulted in a ΔR that varied between 2.36 and 4.36 ohms at crack initiation for tests 17 through 24. For tests 25 through 31 as soon as any question as to possible cracking occurred, the specimen was removed from the testing machine and inspected with a 500x microscope. Using this procedure resistance changes varying between 1.93 and 3.83 ohms were recorded.

Based on these findings it was felt that initial crack detection is a highly subjective failure criterion. Detection can depend on many factors including position of lighting and expertise of the observer. To limit the effects of these factors, all remaining tests were conducted with failure of the gage or total specimen fracture as the failure criterion. Comments are recorded on the rough data sheets concerning physical observations made.

III. EXPERIMENTAL DATA

Figure 5 is a plot comparing several typical tests with an adaption of the manufacturer's characteristic curves for the type NA-01 gage. The data plotted is the results of tests 8,32,36,35 and 3A. These tests were selected because they represent various strain levels between 1364$\mu\varepsilon$ and 4389$\mu\varepsilon$. A comparison of the data with the curves shows that at all strain levels plotted, the gage registers resistance changes that agree closely with expectations.

A complete record of all tests is included in Appendix D. A plot of any of this data will result in curves that closely correspond to the curves in Figure 5. (The exception to this can be noted on tests 14 through 16 when specimen type 2 was used.) A discussion of the various tests is included in Section IV.

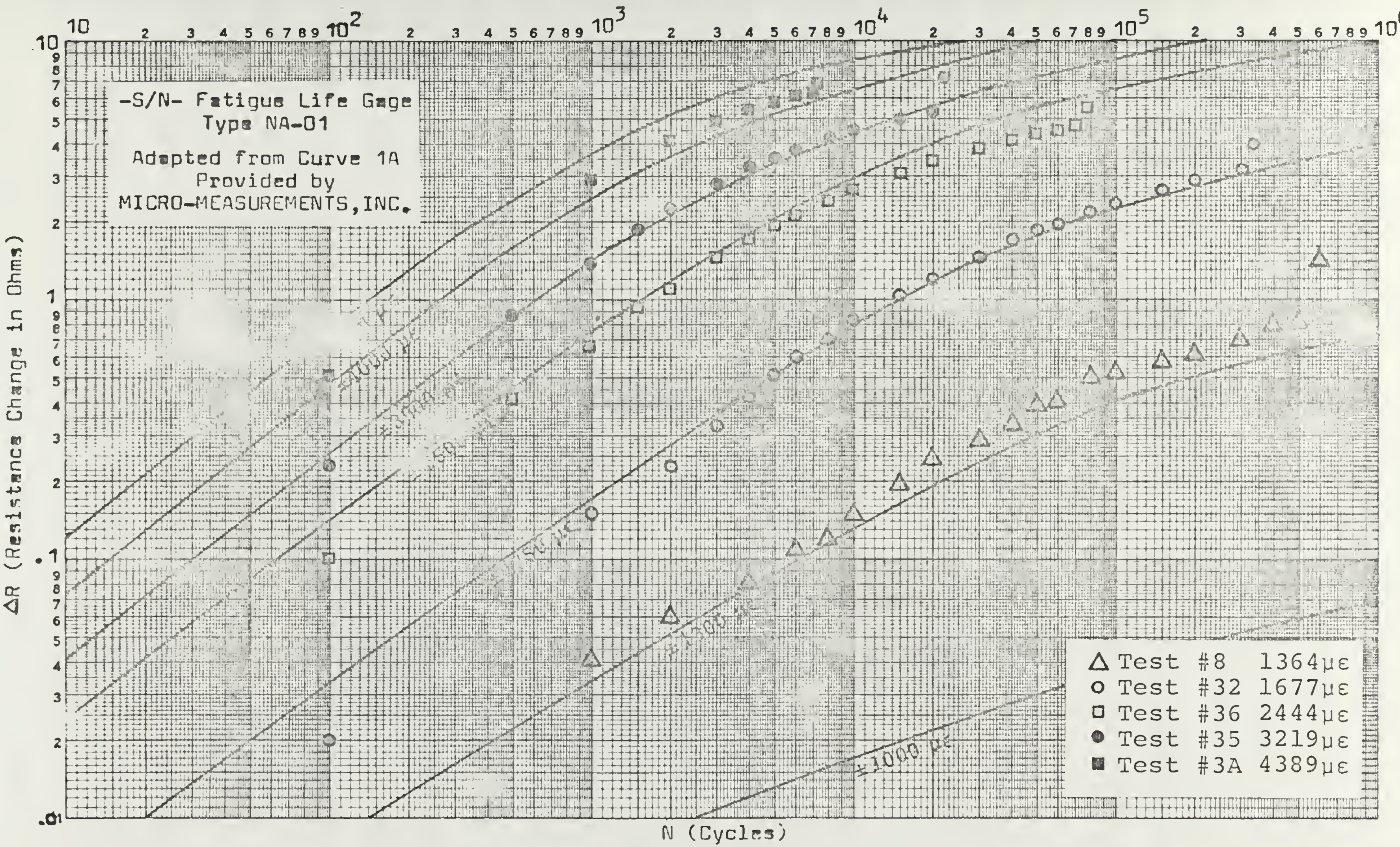

Figure 5. Performance Curve Showing Results of Selected Tests

IV. DISCUSSION OF RESULTS

Figure 5 is a plot comparing data collected with the manufacturer's characteristic curves. It can be observed that the gage reacts in a predictable manner when bonded to 70-30 copper-nickel. However, these plots are tests that were continued until the gage had failed. The ΔR at which the first cracks were observed varied between 0.97 and 3.27 ohms.

The study was accomplished to observe the reaction of the gage when bonded to 70-30 copper-nickel and to correlate the results. The following are comments concerning the various tests completed.

Test #1

This test was conducted using specimen type 1. The strain varied between -2745με and 5509με with a strain level of 4127με . The mean strain was 1382με . At a ΔR of 3.90 ohms, striations were observed in the solder stop. A closer inspection of the surface failed to confirm the existence of any cracking. This had occurred after 2263 cycles. The test was continued and after 4500 cycles a crack was confirmed. The ΔR at this time was 5.13 ohms. The observation of the striations at 3.90 ohms was at a lower resistance than reported in Reference 4. Further experience indicated that the striations noted were cracks in the material.

Tests #2-7

These tests were conducted at varying strain levels to verify results obtained by Rowe (Ref. 4). The strain levels for these tests varied between 3415με and 3970με . All of these tests were conducted using specimen type 1. The ΔR at

the time the first cracks were observed varied between 4.30 and 4.77 ohms. A plot of ΔR vs. N shows that the data closely matches the provided curves.

Test #8

This was the first test conducted at low strain level. It was accomplished at a strain level of $1364\mu\varepsilon$ with a mean strain of $241\mu\varepsilon$, The plot of ΔR vs. N corresponds very closely with the provided curves. No cracks were observed and there was no indication of failure occurring until after 600,000 cycles. At this time the slope of ΔR vs. N increased rapidly. A visual inspection of the upper surface did not reveal any cracks. However, an inspection of the bottom surface showed that cracking had initiated on that side and had propagated upward. This sudden increase in the slope of ΔR vs. N corresponds to what Livingston (Ref. 6) reported in his study. This test was conducted over a three day span. It was noted during this period that the ΔR of the gage showed no change as the gage was rested.

Test #9

This test was conducted at approximately the same level as test number eight to confirm the results obtained. The strain during this test was $1381\mu\varepsilon$ with a mean strain of $236\mu\varepsilon$. A more detailed examination of the surface was conducted during this test. The first cracks were observed on the upper surface after 325,006 cycles. The ΔR was 0.80 ohms. After 547,748 cycles with a ΔR of 0.94 ohms cracking

became visible on the lower surface. After 560,005 cycles the resistance had increased to 1.04 ohms. It was observed that by this time the crack on the lower surface had propagated approximately half way through the specimen. The slope of the data started to increase rapidly. The test was terminated after 564,996 cycles. At that time the resistance had increased to 1.14 ohms.

Test #10

The strain level for this test was 1796$\mu\varepsilon$ with a mean strain of 337$\mu\varepsilon$. The initial striations in the solder stop for this test were observed after 50,001 cycles with a ΔR of 2.40 ohms. The test was continued and between 92,011 and 93,005 cycles a decrease in the resistance, from 2.92 to 2.87 ohms, was observed. An inspection of the gage installation did not show any signs that the bond was breaking loose so the test was continued. The ΔR continued to increase until after 102,997 cycles. At that time the slope of ΔR vs. N began to increase rapidly. The test was terminated after 104,013 cycles. The ΔR at that time was 3.28 ohms. An examination of the specimen again showed that cracking had initiated on the bottom and had propagated upward deep into the specimen.

Test #11

The observation methods used in this test varied from the initial procedures. The test was conducted with a strain level of 1732$\mu\varepsilon$ and a mean strain of 344$\mu\varepsilon$. The initial striations in the solder stop were observed after 37,489 cycles

with a ΔR of 1.67 ohms. At that time the specimen was removed from the testing machine and inspected with a 500x microscope. No cracks were observed. A new coat of solder stop was applied and the test was continued. After 70,009 cycles with a recorded resistance change of 2.00 ohms the striations were again observed. A search of the surface with a 36x lens failed to confirm the existance of any cracks. After 95,013 cycles the ΔR had increased to 2.20 ohms. The striations were still visible in the solder stop. The specimen was removed from the testing machine and the solder stop removed. A dye penetrant was used to check for possible cracks. The results failed to give any indication of cracking so the specimen was remounted and the test resumed. After 120,009 cycles the plot of ΔR vs. N began to increase in slope. An inspection of the lower surface showed that cracking had begun in this area and had propagated upward. The test was terminated after 135,204 cycles with a ΔR of 3.09 ohms.

Test #12

This was the first test conducted using a modified specimen. Specimen type 3 was used for this test with a strain level of $3101\mu\varepsilon$ and a mean strain of $1081\mu\varepsilon$. The first crack was observed after 11,012 cycles with a ΔR of 4.26 ohms. After 13,008 cycles with a ΔR of 4.37 ohms the first cracks were observed on the lower surface. The test was terminated after 20,996 cycles at a ΔR of 5.37 ohms. The major cracking in this specimen occurred on both the top and

bottom surfaces. The characteristic increase in the slope of ΔR vs. N can be noted indicating that gross failure of the material is occurring.

Test #13

This was the first test that was continued until the gage failed. A strain of 3125$\mu\varepsilon$ with a mean strain of 1000$\mu\varepsilon$ was recorded. The ΔR at the time the first crack was observed was 4.36 ohms. This was after 9,992 cycles. The first crack on the lower surface was observed after 15,005 cycles. The ΔR at that time was 4.84 ohms. After completing 20,301 cycles the slope of the curve began to increase. The gage failed after 20,766 cycles due to a crack penetrating the backing material and breaking the grid.

Tests #14-16

The specimens used for these tests were specimen type 2 (Fig.2). In this case the stress raiser on the lower surface had been removed. The only stress raiser that existed in this specimen was on the sides. The initial data shows that the plot of ΔR vs. N closely follows the characteristic curves. However, as the number of cycles increased the slope of the ΔR vs. N began to decrease. At that time no reason could be observed for this change in the slope. During test #14 after 66,626 cycles the specimen physically parted at the clamping block. The same type of behavior was noted in both test 15 and 16. The stress raisers that were cut in the sides of the specimen were insufficient to make this the area of maximum

strain. Accordingly, the remainder of the tests was conducted using specimen type 3.

Tests #17-24

The strain level for these tests varied between 2097$\mu\varepsilon$ and 3702$\mu\varepsilon$. The object of all of these tests was to try to obtain a ΔR for the initiation of cracking. At the first observation of cracks the test was considered complete. In these tests the ΔR varied between 2.74 and 4.21 ohms.

Tests #25-30

The initial failure criterion for tests numbers 1 through 30 was initial crack detection. The strain level for tests 25 through 30 varies from 3151$\mu\varepsilon$ to 4026$\mu\varepsilon$. The ΔR at which the first crack was observed varied between 1.93 and 3.93 ohms. After observing the results of this series of tests, it was concluded that the failure criterion being used was not satisfactory. The initial detection of cracks depended on the experience level of the observer. To limit the effect of this factor it was decided that all subsequent tests would be terminated at either failure of the gage or specimen fracture which was indicated by penetration of a crack more than half way through the thickness of the specimen. Accordingly, all of the specimens in this series of tests, with the exception of specimen 29, were remounted in the testing machine and cycled to gage failure. It is possible that the strain levels for the additional cycling of the specimens may have varied slightly due to positioning of the specimen in the clamping block.

However, the curves of ΔR vs. N do not indicate any major change in the strain level. It was noted in the plots of data for tests number 26 and 27 that the characteristic increase in the slope of the curve of ΔR vs. N is not observed. This can possibly be attributed to the rapidity of crack propagation at the higher strain levels. In both of these cases approximately 500 cycles were completed after the last resistance reading until the gage failed.

Test #31

Test number 31 was conducted on another of the specimens that was remounted in the testing machine for additional cycling. The strain level for this test was 3908$\mu\varepsilon$ with a mean strain of 1146$\mu\varepsilon$. The first crack in this specimen was observed after 806 cycles. The ΔR at that time was 2.03 ohms. After 8902 cycles had been completed, it was observed that a slight drop in the resistance of the gage had occurred. This was the same type of phenomenon that had occurred during test number ten. After 9095 cycles an additional decrease in the resistance change was observed. To try to get an idea as to what was causing this, the specimen was hand cycled through additional cycles. In the next 449 cycles it was observed that two additional decreases in resistance occurred. For the rest of the test the gage resistance continued to increase until the gage broke at approximately 10,135 cycles.

Tests #32-36

These tests were all terminated at failure of the gage. The strain levels varied between 1677$\mu\varepsilon$ and 3219$\mu\varepsilon$. In all

of these tests the first cracks were observed after only a relatively small percentage of the total number of cyles to failure. A plot of the data shows that even after the first cracks are observed the gage continues to record in a predictable manner. On tests number 33 and 34 it was noted that the running plot of the data appeared about 200$\mu\varepsilon$ higher than would be expected.

Tests #1A-5A

These gages were mounted to observe the effect of a rest period on the gages. All of the gages were mounted using Eastman 910 Adhesive and protected with a coat of Polyurethane. At random periods over several months the specimens were cycled through various numbers of cycles. In all cases the decrease in ΔR during a rest period did not exceed 0.09 ohms. For tests number 3A and 5A which were cycled to failure the plot of data corresponds to the manufacturer's characteristic curves. In all cases the bond of the gage appears sound after four months.

V. CONCLUSIONS

The S/N Fatigue Life Gage was developed to provide a method by which incipient fatigue failure could be predicted. It was the objective of this study and that of Rowe (Ref. 4) to try to study the ΔR at crack initiation of 70-30 copper-nickel with the expectation that a fairly definite ΔR would be observed regardless of the details of the previous strain history. This expectation was not realized. As experience in detection of cracks improved, small surface cracks were noted very early in specimen life. These cracks were observed over the width of the specimen except under the gage. Even though the specimen was cracked, the gage continued to give the characteristic curve of ΔR vs. N shown in Figure 7. This curve began to vary when the cracks had propagated deeply into the specimen. The gages finally failed when one of the cracks penetrated the glass-fiber/epoxy laminate of the gage and broke the grid.

The plotted data of all tests show that the resulting curve of ΔR vs. N closely follows the trend of curves based on the manufacturer's tests. This was true of all specimen types used. In most of the tests conducted, a rapid increase in the slope of ΔR vs. N was obvious just prior to the gage failure. However, for tests 26 and 27 this increase in slope was not observed.

As reported by Triebes (Ref. 7) the existence of a non-zero mean strain does not appear to have any adverse effects. All tests conducted during this study were cycled about non-zero mean strains. The resulting data corresponds closely with the predicted characteristics.

The effect of a rest period on the gage does not appear to have any significant effect. Tests 1A through 5A were conducted on specimens which had the gages mounted for periods of from one to four months. A maximum decrease of 0.09 ohms resistance was recorded as the gages were tested. It is possible that a slight variation in the clamping of the specimen in the machine may account for part of this difference. For the two specimens that were tested to failure the curves of ΔR vs. N agree closely with the manufacturer's curves.

The mounting procedure as described in Appendix B appears satisfactory. All gages during this study were mounted with Eastman 910 Adhesive. None of the gages appeared to break loose from the specimen during testing. On the specimens that were cycled to total failure the cracking all occurred about mid-gage. The gage remained bonded to the specimen after the gage had broken. Two specimens were subjected to increasing levels of strain. At strain levels in excess of 13,000$\mu\varepsilon$ the gages did shear loose from the specimen. However, at this level of strain this is expected (Ref. 8). For the aging tests the same procedures were followed. After four months no appearance of bonding failure was observed.

After evaluating all tests, it was concluded that the gage still holds much promise for use on copper-nickel. However, the use of the gage on systems subjected to unknown strain levels does not appear feasible at this time.

APPENDIX A

DESCRIPTION OF GAGE

The S/N Fatigue Life Gage has the general appearance of a common foil strain gage (Figure 6). It is constructed of a specially treated constantan (approximately 55% copper, 45% nickel) foil grid encapsulated in a glass-fiber/epoxy laminate. The gage is available in various sizes with either solder turrets or integral leads. Application of the gage is made using standard strain gage adhesives and techniques (Ref. 1).

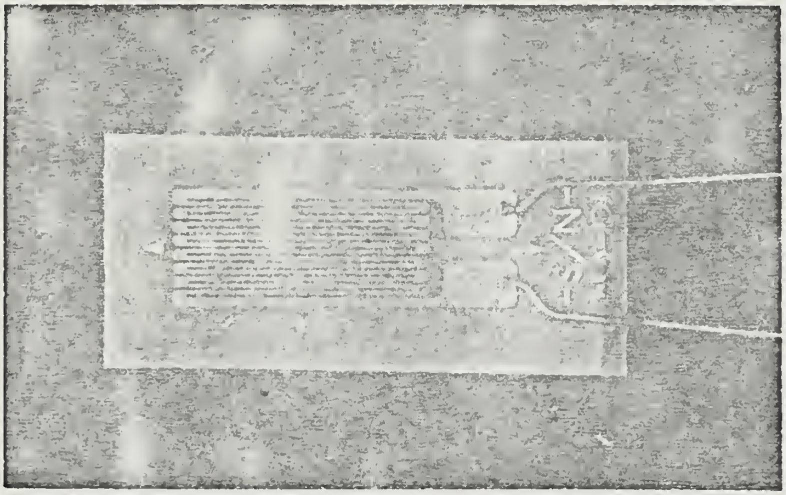

Figure 6 - S/N Fatigue Life Gage

The gage is made to be bonded to the area where fatigue failure is expected. When strains occur, a permanent and irreversible increase in the resistance of the grid occurs. Because the resistance change is permanent, only an intermittent monitoring of the gage is required.

The resistance change is a function of the grid material, grid configuration, physical dimensions, heat-treatment,

cold-working and residual stresses in the grid material of the gage. By maintaining careful control of these parameters the inventor claims that the required gage characteristics can be obtained (Ref. 2).

The fatigue life gage can initially be used as a conventional strain gage. The initial gage resistance is approximately 100 ohms with a gage factor of 2.04. As the resistance of the gage changes, however, so does the gage factor. With a resistance change of three ohms the gage factor will increase to approximately 2.07. Beyond this level of resistance change the gage factor increases rapidly. As a result the gage will no longer give accurate strain indications and should not be used as a strain gage.

When using the gage, consideration must be given to temperature variations. The temperature coefficient of resistance of the NA series gages varies as a function of the fatigue damage sustained. The resistance coefficient varies between $-20\mu\Omega/\Omega/^\circ F$ to $-34\mu\Omega/\Omega/^\circ F$ in the temperature range of 75° - 150°F. To eliminate the error due to temperature variations it is recommended that all measurements be made at or near 75°F.

The resistance change of the sensor is a result of cumulative fatigue damage caused by varying strains. Figure 7 is a plot showing ΔR (Resistance change) vs. N (Number of cycles) at various strain levels. The curves are a result of cycling about a zero mean strain. Experiments have shown, however,

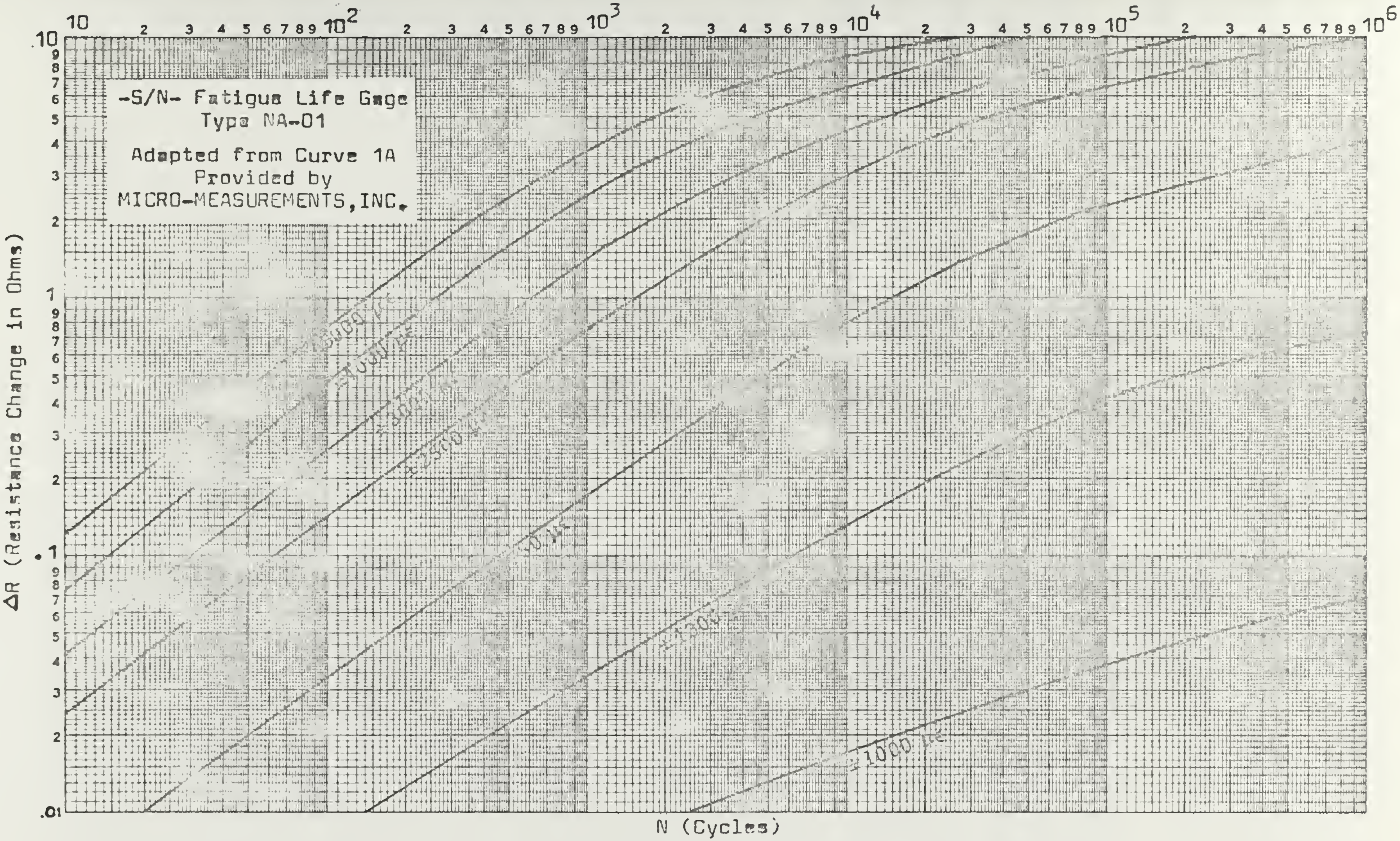

Figure 7. Performance Curves of Type NA-01 Fatigue Life Gage

that the same curves also correspond fairly closely to cycling about a non-zero mean strain providing the total strain amplitude ($2x\varepsilon_R$) is not too small (Ref. 3). Triebes (Ref. 7) concluded that the performance of the gage is virtually unaffected by the application of a mean load.

Since the gage response is basically independent of the mean strain, the ΔR caused by tension-tension or compression-compression at a given strain level is the same as for reversed bending. It is also noted that the curves are a plot of ΔR vs. N and as a result do not depend on the nature of the material to which they are bonded.

APPENDIX B

PREPARATION OF SPECIMEN

All test specimens used in this study were fabricated from 0.375 inch 70-30 copper-nickel plate. The original specimen used (Figure 1) was the "W. T. Bean Plain Fatigue Specimen." This specimen was chosen because:

1. The manufacturer's predicted gage characteristics curves were based on it;

2. The strain was known to be concentrated in the reduced area;

3. The specimen was designed to fit the machine being used;

4. Initial data collected (Ref. 4) was obtained using this specimen.

For reasons listed in Section II the specimen configuration was later changed to that shown in Figure 3.

The specimens were all obtained from two 24 inch by 12 inch by 0.375 inch 70-30 copper-nickel plates. The desired length and width were obtained by machining with a shaper. The reduced section and finished surface were produced by milling at slow speed to avoid specimen distortion.

The procedures used in preparing the specimen surface and gage for testing were those recommended by References 3 through 5 inclusive. The only modifications required were in the mounting of the gage. The procedures were as follows:

1. Clean the specimen surface with Chlorothene NU Degreaser;

2. Dip one end of a one inch piece of 320 grit silicon carbide paper into metal conditioner (M-Prep

Conditioner A), lap all surfaces, and remove residue with one stroke of a clean tissue;

3. Dip one end of a one inch piece of 400 grit silicon carbide paper into metal conditioner, lap the flat surface where the gage is to be applied, and remove residue with one stroke of a clean tissue;
4. Layout gage location using a 6-H pencil (For specimen type 1 this was 1/16 inch toward the clamped end from the center-line of the reduced section. For specimens type 2 and 3 this was the center of the reduced section);
5. Clean the mounting surface of the specimen with metal conditioner and a cotton swab and wipe dry;
6. Wash hands;
7. Clean the mounting surface of the specimen with a cotton swab and isopropyl alcohol and wipe dry with one swipe of a clean tissue (Extreme care should be taken to ensure that the surface of the specimen is absolutely clean prior to the application of the gage. Failure to obtain this goal may result in poor bonding of the gage and lead to erroneous strain indications.);
8. With a circular motion and light pressure applied by the finger, lap the bonding surface of the gage in a fine pumice powder on a clean surface (This action ensures that the bonding surface of the gage is slightly roughened to provide for a better bond.);

9. Attach a small piece of cellophane tape to the surface of the gage (This tape is used to position the gage over the specimen.);

10. Clean the back of the gage with a cotton swab dampened with isopropyl alcohol (This step ensures that all of the pumice powder is removed and leaves a clean bonding surface.);

11. Position the gage using the scribe marks on the specimen (In this study the lead end of the gage was towards the clamping end of the specimen.)(Fig. 8);

12. Carefully mask the area around the gage with masking tape to avoid excessive flow of adhesive;

13. Apply a thin coat of M-Line Catalyst to the back of the gage and allow it to dry for one minute;

14. Apply two (2) drops of Eastman 910 adhesive to the specimen;

15. Place the gage in position over the surface of the specimen and force it into place with one stroke of thin teflon sheet;

16. Within one second press the gage firmly into position with a thumb or forefinger and hold for thirty seconds (This not only forces the gage firmly into position but the heat from the finger helps cure the adhesive and ensures a solid bond.);

17 Wait for two minutes and remove the cellophane tape from the surface of the gage (Applying a light coat of rosin solvent will help to loosen the tape.);

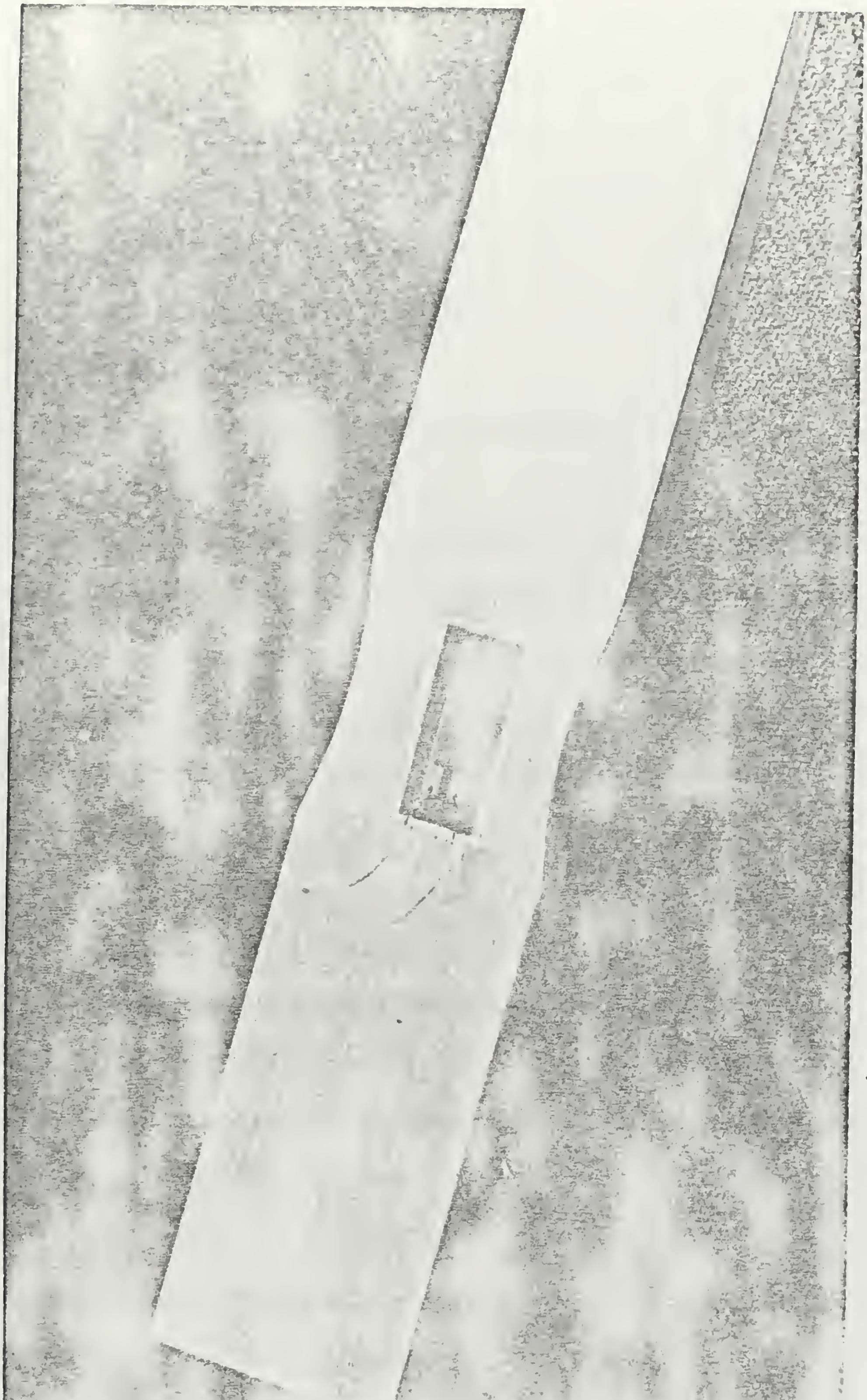

Figure 8. Mounted Gage Ready for Testing

18. Apply a thin coat of M-Coat A (Polyurethane) and allow to dry for ten minutes (The M-Coat A is a water-proofing. If allowed to stand exposed to the air the Eastman 910 has a tendency to absorb moisture and this could affect the bond. This is particularly important if the specimen is not to be tested immediately.);

19. Remove the masking tape and apply a coat of solder stop and allow it to dry for one minute.

At this stage the gage is mounted and the specimen is ready for testing. To complete the preparation for testing:

1. Place the specimen in position (Fig. 4) in the clamping block;
2. Cover the surface of the gage to protect it from solder spatter;
3. Solder connect the gage leads to the copper wire leading to the terminal strip;
4. Remove the protective cover from the gage.

The initial resistance in the neutral position was recorded. The gage was then connected to the Budd/Strainsert and checked for drift. A drift in the strain readings would be considered evidence that a poor bond existed. With all of the preliminary checks complete the assembly was ready for testing.

APPENDIX C

DESCRIPTION OF APPARATUS

S/N Fatigue Machine

All of the tests conducted for this study were done on a modified W. T. Bean S/N Fatigue Machine (Figures 4 and 9). The machine is a constant displacement device designed to be used for low-cycle fatigue studies. The specimen is positioned to be strained as a cantilever beam. By repositioning the shim plate on the clamping block the specimen can be tested in reversed bending, all tension or all compression (Ref. 6).

The original machine was modified to allow for additional strain ranges without having to modify the specimen configuration. The modified base made it easier to change the strain levels. The modifications consisted of:

1. The fabrication of a new base plate;
2. The relocation of the motor and controller;
3. The addition of a moveable clamping block.

The block can be moved by a fabricated tailstock. It slides between two rails. During the test the block is held rigid by a lock bolt that moves in a traveling slot in the base and by an adjustable gib plate.

S/N Fatigue Life Gages

The gages used were provided by Micro-Measurements, Inc., Romulus Michigan. They were the FWA-01 series with a constantan grid and a glass-fiber/epoxy laminate. The initial resistance of the gages was $100.0\Omega \pm 0.2\%$ with a gage factor of 2.04. All gages used were from lots ZD-A12AP39 or ZD-A12AP41 (Figure 6).

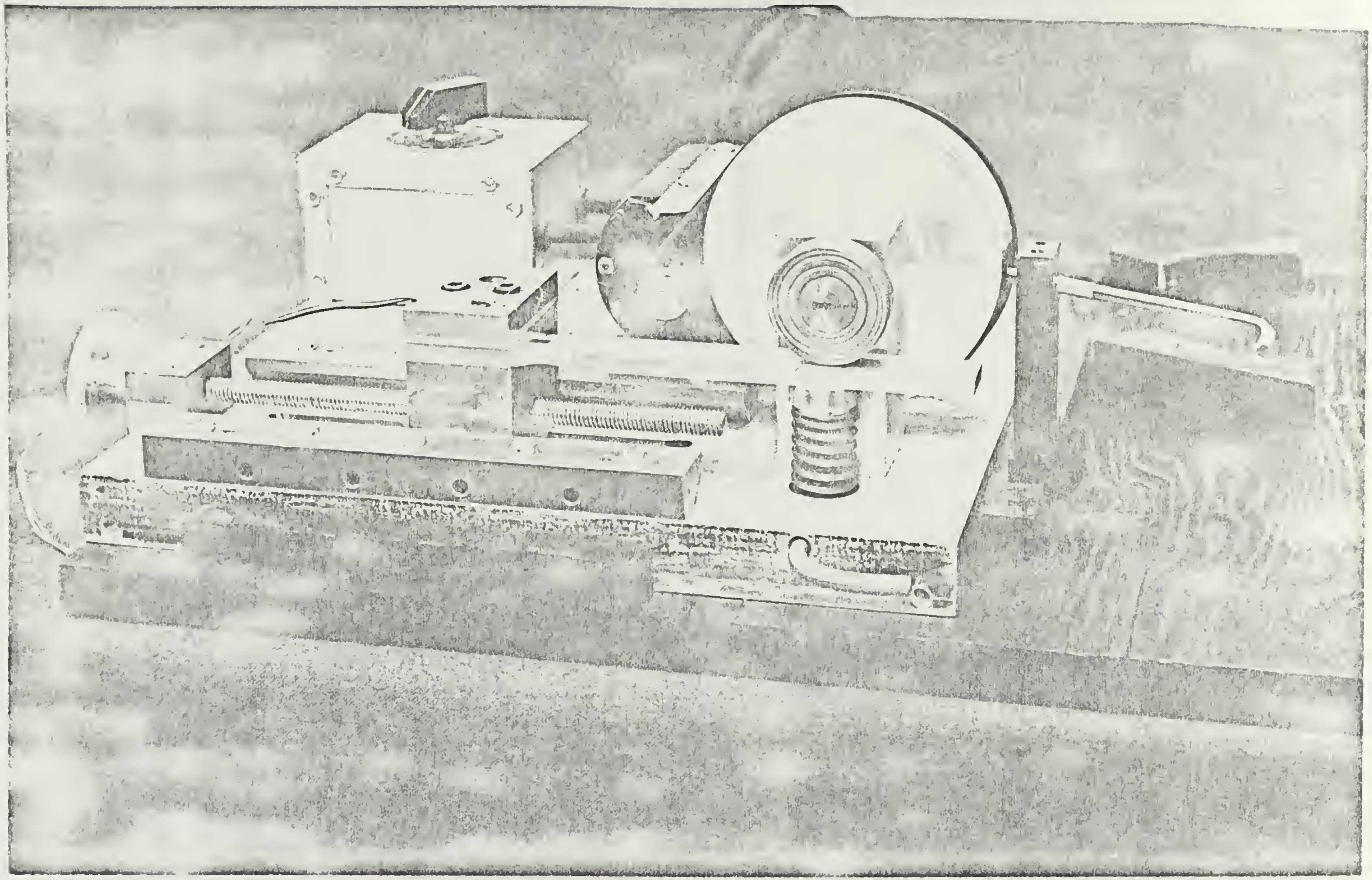

Figure 9. Test Set Up Showing Modifications to Fatigue Machine

Cu-Ni Specimens

All specimens used were fabricated from two copper-nickel plates. The chemical composition of the plates was:

	Cu %	Ni %	Zn %	Fe %	Mn %	Pb %	P %	S %	Ti %	Other Elements %
Plate 1	68.37	30.50	0.09	0.62	0.42	<0.01	<0.01	<0.01	<0.10	<0.50
Plate 2	68.61	30.30	0.05	0.43	0.60	<0.05	0.007	0.005	----	<0.50

The mechanical properties were as follows:

Plate 1

Yield strength	20 KSI
Tensile strength	52.3 KSI
Elongation in two inches	48%
Young's modulus	21×10^6 PSI
Reduction in area	73%

Plate 2

Yield strength	19.5 KSI
Tensile strength	53.9 KSI
Elongation in two inches	45%
Young's Modulus	25.9×10^6 PSI
Reduction in area	70.1%

The chemical and mechanical properties for both plates were provided by Mr. H. G. MacKerrow, Head, Metallurgical Laboratory Branch, San Francisco Bay Naval Shipyard, Vallejo, California.

The following equipment was also used:

1. Budd/Strainsert Portable Strain Indicator
2. General Radio Co. Decade Resistor

3. W. T. Bean Co. S/N Meter Null Indicator

4. Hewlett Packard Co. Tachometer Head

5. Power Designs Inc. Regulated DC Power Supply

6. Hewlett Packard Co. Electronic Counter

7. Eveready mini-max batteries

Items four through seven were used in the counting circuit for the tests.

A complete description of items one through seven can be found in Reference 4. Figure 10 is a photograph of the apparatus.

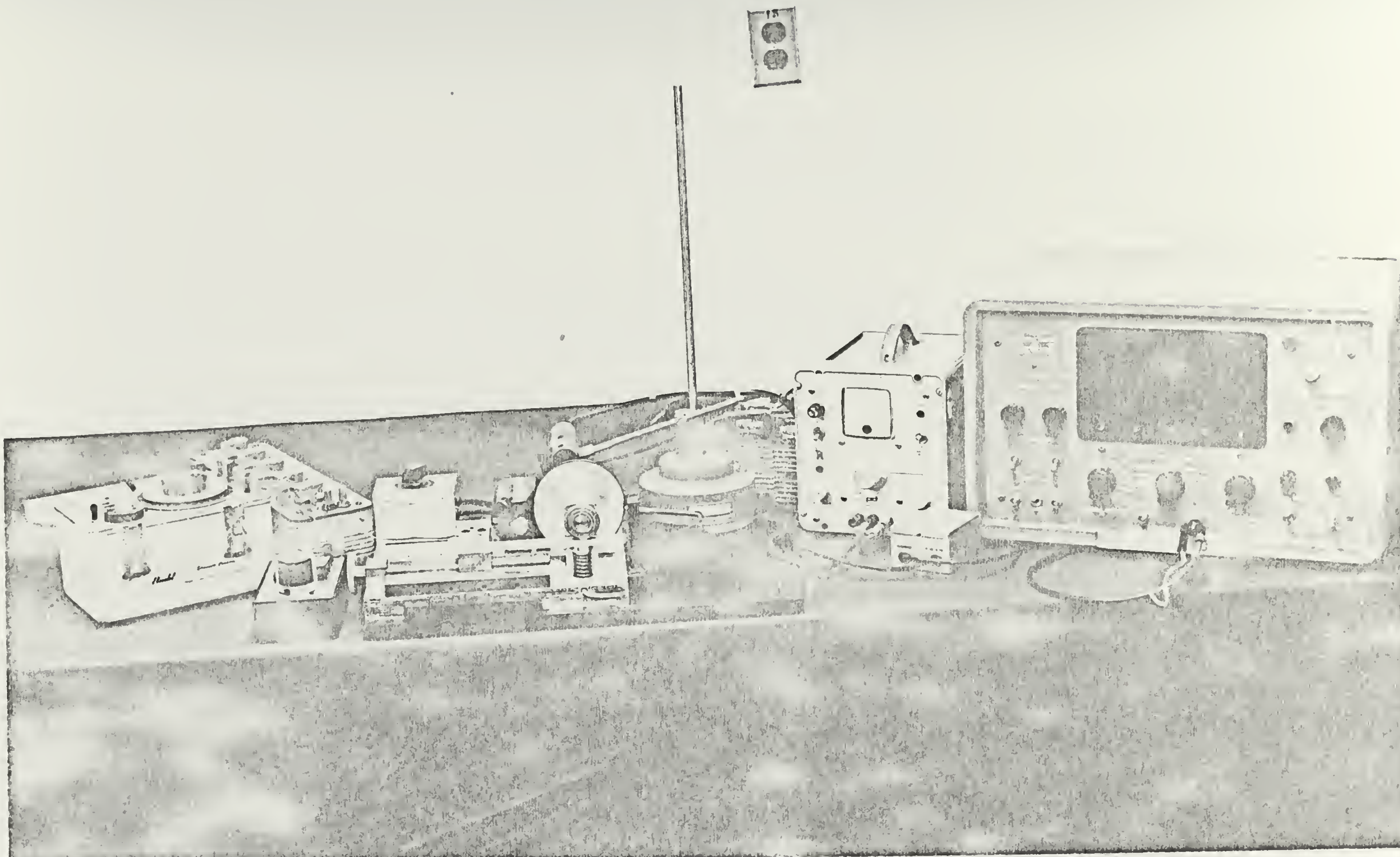

Figure 10. Test Apparatus Used for All Tests

APPENDIX D

TABULATION OF DATA

Test #1

Strain Level: ±4127με

Mean Strain: 1382με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0			142	-2640	5796	4218
1	100.09		358	-2740	5588	4164
6			608	-2738	5564	4151
7			737	-2771	5481	4126
8			749	-2749	5483	4126
9			779	-2740	5496	4118
10	100.23		810	-2741	5504	4123
100	100.68	0.45				
493	101.87	1.64				
1000	102.77	2.54				
1497	103.46	3.23				
2007	103.97	3.74				
2263	104.13	3.90	First crack observed			
2504	104.31	4.08				
2759	104.52	4.29				
2994	104.66	4.43				
3260	104.79	4.56				
3499	104.88	4.65				
3753	104.99	4.76				
4001	105.08	4.85				
4247	105.22	4.99				
4500	105.36	5.13				

Test #2

Strain Level: $\pm 3926\mu\varepsilon$

Mean Strain: $1302\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.12		361	-2496	5676	4086
1	100.19		572	-2611	5450	4031
6			905	-2629	5256	3943
7			911	-2593	5265	3929
8			988	-2622	5216	3919
9			1032	-2625	5218	3922
10	100.25		1061	-2613	5217	3915
100	100.62	0.37				
1005	102.63	2.38				
1507	103.25	3.00				
2000	103.71	3.46				
2498	104.03	3.78				
2755	104.22	3.97				
2998	104.33	4.08				
3497	104.54	4.29				
3749	104.69	4.44				
3999	104.78	4.53				
4252	104.86	4.61	First crack observed			
4500	104.96	4.71				
4750	104.98	4.73				
5006	105.09	4.84				
5256	105.20	4.95				
5508	105.26	5.01				
5753	105.29	5.04				
6004	105.38	5.13				
6250	105.41	5.16				

Test #3

Strain Level: $\pm 3970\mu\varepsilon$

Mean Strain: $1283\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.05		088	-2623	5560	4092
1	100.36		1582	-4004	4098	4051
6			505	-2653	5313	3983
7			587	-2678	5256	3967
8			612	-2672	5260	3966
9			671	-2686	5267	3977
10	100.22		724	-2672	5237	3955
100	100.58	0.36				
997	102.86	2.64				
1496	103.56	3.34				
1999	103.88	3.66				
2500	104.30	4.08				
2748	104.38	4.16				
3000	104.57	4.35				
3257	104.69	4.47				
3496	104.81	4.59				
3750	104.87	4.65				
3998	104.99	4.77	First crack observed			

Test #4

Strain Level: $\pm 3539\mu\varepsilon$

Mean Strain: $1116\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.06		109	-2437	4771	3604
1	100.09		145	-2387	4763	3575
6			319	-2375	4714	3545
7			1141	-3163	3933	3548
8			399	-2379	4693	3536
9			440	-2394	4668	3531
10	100.15		485	-2421	4652	3537
100	100.47	0.32				
1002	102.12	1.97				
2002	103.08	2.93				
3003	103.71	3.56				
3495	103.94	3.79				
4006	104.12	3.97				
4505	104.30	4.15				
5006	104.45	4.30	First crack observed			
5556	104.59	4.44				
6002	104.70	4.55				

Test #5

Strain Level: $\pm 3415\mu\varepsilon$

Mean Strain: $1183\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.24		916	-2124	4862	3493
1	100.28		1135	-2250	4656	3451
6			1221	-2181	4668	3425
7			1271	-2204	4629	3417
8			1308	-2208	4610	3409
9			1329	-2207	4620	3419
10	100.33		1370	-2222	4588	3405
100	100.63	0.30				
1009	102.12	1.79				
1993	102.99	2.66				
3012	103.59	3.26				
3504	103.85	3.52				
4007	104.04	3.71				
4507	104.20	3.87				
5003	104.36	4.03				
5501	104.48	4.15				
5998	104.69	4.36	First crack observed			
6497	104.71	4.38				
6998	104.78	4.45				
7500	104.90	4.57				
8001	104.99	4.66				
8504	105.05	4.72				

Test #6

Strain Level: $\pm 3695\mu\varepsilon$

Mean Strain: $1249\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.18		625	-2397	5177	3787
1	100.20		772	-2452	5036	3744
6			970	-2430	4978	3704
7			1172	-2584	4803	3694
8			1069	-2453	4921	3687
9			1128	-2488	4888	3688
10	100.31		1120	-2451	4948	3700
100	100.64	0.33				
1007	102.14	1.83				
2006	103.27	2.96				
2498	103.66	3.35				
3006	103.90	3.59				
3504	104.20	3.89				
3997	104.41	4.10				
4502	104.61	4.30				
4998	104.76	4.45	First crack observed			
5497	104.90	4.59				
5999	105.00	4.69				
6501	105.13	4.82				
7002	105.31	5.00				
7490	105.38	5.07				
8012	105.48	5.17				

Test #7

Strain Level: $\pm 3678\mu\varepsilon$

Mean Strain: $1207\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.03		-025	-2445	4956	3701
1	100.06		015	-2729	4700	3715
6			-049	-2467	4898	3683
7			-002	-2484	4892	3688
8			060	-2482	4878	3680
9			098	-2472	4867	3670
10	100.15		121	-2460	4873	3667
100	100.50	0.35				
988	102.22	2.07				
1495	102.77	2.62				
2008	103.24	3.09				
3007	103.84	3.69				
3492	104.12	3.97				
4007	104.36	4.21				
4493	104.54	4.39				
5004	104.69	4.54	First crack observed			
5497	104.83	4.68				
6003	104.94	4.79				
6494	105.07	4.92				

Test #8

Strain Level: $\pm 1364\mu\varepsilon$

Mean Strain: $241\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.18		-049	-1122	1646	1384
1	100.16		-022	-1138	1613	1376
6			-016	-1125	1603	1364
7			-010	-1124	1599	1362
8			-005	-1132	1595	1364
9			000	-1137	1592	1365
10	100.18		-012	-1123	1604	1364
100	100.18	0.00				
1024	100.22	0.04				
2011	100.24	0.06				
4004	100.26	0.08				
6009	100.29	0.11				
7981	100.30	0.12				
10002	100.33	0.15				
14992	100.37	0.19				
20014	100.42	0.24				
30014	100.46	0.28				
39993	100.51	0.33				
50005	100.55	0.37				
59997	100.58	0.40				
70050	100.63	0.45				
80004	100.67	0.49				
90013	100.68	0.50				
99994	100.70	0.52				
149995	100.73	0.55				
200026	100.80	0.62				
300016	100.88	0.70				
399986	100.96	0.78				
499974	100.98	0.80				
599986	101.62	1.44	First crack observed			
609965	102.00	1.82				

Test #9

Strain Level: $\pm 1381 \mu\varepsilon$

Mean Strain: $236 \mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.06		-435	-1141	1674	1408
1	100.09		-399	-1163	1633	1398
6			-392	-1147	1619	1383
7			-381	-1153	1603	1378
8			-388	-1148	1612	1380
9			-392	-1146	1622	1384
10	100.09		-384	-1142	1613	1378
100	100.10	0.01				
1984	100.14	0.05				
3997	100.16	0.07				
6000	100.20	0.11				
8012	100.24	0.15				
9999	100.26	0.17				
14998	100.30	0.21				
20006	100.35	0.26				
30011	100.41	0.32				
39995	100.46	0.37				
50005	100.50	0.41				
60002	100.52	0.43				
70003	100.56	0.47				
79998	100.59	0.50				
90001	100.62	0.53				
99995	100.65	0.56				
125000	100.70	0.61				
150005	100.73	0.64				
175000	100.76	0.67				
200008	100.78	0.69				
225001	100.80	0.71				
249999	100.83	0.74				
275000	100.87	0.78				
299989	100.88	0.79				
325006	100.89	0.80	First crack observed			
349997	100.90	0.81				
374984	100.92	0.83				
400040	100.93	0.84				
425006	100.95	0.86				
450008	100.98	0.89				
475007	100.98	0.89				
499999	100.99	0.90				
524986	101.01	0.92				
547748	101.03	0.94	Crack visible on under surface			
549998	101.03	0.94				
560005	101.13	1.04				
564996	101.23	1.14				

Test #10

Strain Level: $\pm 1796 \mu\varepsilon$

Mean Strain: $337 \mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.18		-2492	-1330	1977	1654
1	100.19		-2490	-1452	2180	1816
6			-2425	-1465	2127	1796
7			-2432	-1458	2134	1796
8			-2425	-1463	2133	1798
9			-2410	-1472	2120	1796
10	100.21		-2415	-1457	2130	1794
100	100.21					
988	100.40	0.19				
1999	100.57	0.36				
4025	100.83	0.62				
6001	101.03	0.82				
8001	101.24	1.03				
9998	101.36	1.15				
15004	101.66	1.45				
20004	101.86	1.65				
30007	102.18	1.97				
40005	102.41	2.20				
50001	102.61	2.40	First crack observed			
60001	102.76	2.55				
69988	102.83	2.62				
80320	102.96	2.75				
90009	103.08	2.87				
92011	103.13	2.92				
93005	103.08	2.87				
94020	103.10	2.89				
95999	103.13	2.92				
98022	103.14	2.93				
100003	103.22	3.01				
101019	103.26	3.05				
101997	103.28	3.07				
102997	103.36	3.15				
104013	103.49	3.28				

Test #11

Strain Level: $\pm 1732 \mu\varepsilon$

Mean Strain: $344 \mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.10		-2750	-1310	2274	1792
1	100.15		-2622	-1378	2140	1759
6			-2574	-1360	2104	1732
7			-2561	-1374	2099	1737
8			-2555	-1357	2097	1727
9			-2540	-1369	2086	1728
10	100.16		-2531	-1390	2078	1734
100	100.21	0.05				
998	100.34	0.18				
2005	100.46	0.30				
4005	100.65	0.49				
6001	100.81	0.65				
8004	100.92	0.76				
10000	101.04	0.88				
15006	101.24	1.08				
20001	101.40	1.24				
30012	101.68	1.52				
35004	101.74	1.58				
37489	101.83	1.67				
40013	101.84	1.68				
44986	101.89	1.73				
50004	101.97	1.78				
55006	102.03	1.84				
60000	102.09	1.90				
65012	102.15	1.96				
70009	102.19	2.00	First crack observed			
75003	102.25	2.06				
80004	102.29	2.10				
85007	102.32	2.13				
90007	102.36	2.17				
95013	102.39	2.20				
99995	102.45	2.26				
105000	102.45	2.26				
120009	102.91	2.72				
135204	103.28	3.09				

Test #12

Strain Level: $\pm 3101 \mu\varepsilon$

Mean Strain: $1081 \mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.72		-3892	-2023	4523	3273
1	99.72		-1715	-2103	4333	3218
6			-1532	-1980	4215	3098
7			-1515	-2033	4211	3122
8			-1470	-2013	4193	3103
9			-1422	-2021	4160	3091
10	99.80		-1428	-2012	4173	3093
100	100.00	0.20				
1007	101.23	1.43				
2000	101.89	2.09				
2995	102.39	2.59				
4000	102.76	2.96				
5002	102.97	3.17				
6003	103.32	3.52				
7001	103.49	3.69				
7996	103.66	3.86				
9002	103.78	3.98				
10008	103.93	4.13				
11012	104.06	4.26	First crack observed			
12013	104.10	4.30				
13008	104.17	4.37	Crack observed on the bottom surface			
13999	104.28	4.48				
15006	104.38	4.58				
15998	104.46	4.66				
16994	104.52	4.72				
17996	104.59	4.79				
18995	104.66	4.86				
20011	104.73	4.93				
20996	105.17	5.37				

Test #13

Strain Level: $\pm 3125\mu\varepsilon$

Mean Strain: $1000\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.02		-656	-1956	4546	3251
1	100.09		-320	-2118	4258	3188
6			-167	-2088	4207	3148
7			-058	-2094	4110	3102
8			-060	-2120	4163	3142
9			-031	-2118	4122	3120
10	100.16		-017	-2113	4112	3113
100	100.32	0.16				
1003	101.52	1.36				
2002	102.31	2.15				
3008	102.87	2.71				
4005	103.25	3.09				
4998	103.55	3.39				
5998	103.81	3.65				
6997	104.02	3.86				
7998	104.21	4.05				
8998	104.39	4.23				
9992	104.52	4.36	First crack observed			
11000	104.63	4.47				
11987	104.73	4.57				
13005	104.82	4.66				
14001	104.91	4.75				
15005	105.00	4.84	Crack observed on bottom surface			
16001	105.09	4.93				
16996	105.19	5.03				
18000	105.25	5.09				
19005	105.35	5.19				
20301	105.50	5.34				
20768	Gage failed					

Test #14

Strain Level: $\pm 1727\mu\varepsilon$

Mean Strain: $260\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.30		1092	-1217	1531	1374
1	100.30		1038	-1458	1987	1723
6			942	-1484	1975	1730
7			931	-1473	1992	1733
8			928	-1460	1999	1730
9			935	-1447	1995	1721
10	100.30		948	-1463	1983	1723
100	100.32	0.02				
1008	100.44	0.14				
1998	100.54	0.24				
2999	100.64	0.34				
4000	100.72	0.42				
4999	100.80	0.50				
5998	100.87	0.57				
7002	100.92	0.62				
8003	100.98	0.68				
9001	101.00	0.70				
10003	101.05	0.75				
14999	101.28	0.98				
20021	101.40	1.10				
30022	101.60	1.30				
40009	101.74	1.44				
50007	101.86	1.56				
60008	101.89	1.59				
65005	101.89	1.59				
66626	Cracked at clamping block					

Test #15

Strain Level: $\pm 2172\mu\varepsilon$

Mean Strain: $433\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.25		715	-1643	2658	2151
1	100.25		745	-1747	2634	2191
6			805	-1748	2596	2172
7			819	-1761	2588	2175
8			843	-1778	2566	2172
9			833	-1756	2579	2168
10	100.28		819	-1741	2606	2174
100	100.32	0.04				
989	100.71	0.43				
2004	101.03	0.75				
3006	101.24	0.96				
4007	101.49	1.21				
5007	101.64	1.36				
6006	101.79	1.51				
6993	101.92	1.64				
8000	102.00	1.72				
9006	102.10	1.82				
9999	102.20	1.92				
12496	102.41	2.13				
14993	102.57	2.29				
17496	102.72	2.44				
20685	102.82	2.54				
22500	102.90	2.62				
25000	102.98	2.70				
27506	103.08	2.80				
29997	103.19	2.91	First crack observed			
32498	103.24	2.96				
34997	103.30	3.02				
37512	103.34	3.06				
39992	103.44	3.16				
41264	103.49	3.21				
42001	103.51	3.23				
43003	103.55	3.27				
43994	103.56	3.28				
45000	103.60	3.32	Cracked at clamping block			

Test #16

Strain Level: $\pm 2104\mu\varepsilon$

Mean Strain: $426\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.14		142	-1670	2614	2142
1	100.15		197	-1692	2571	2132
6			263	-1681	2533	2107
7			277	-1695	2513	2104
8			289	-1702	2511	2107
9			293	-1682	2518	2100
10	100.19		304	-1684	2516	2100
100	100.21	0.02				
1000	100.58	0.39				
1993	100.82	0.63				
2998	101.06	0.87				
4003	101.24	1.05				
5000	101.42	1.23				
5997	101.54	1.35				
7004	101.67	1.48				
7999	101.78	1.59				
9001	101.89	1.70				
10008	101.98	1.79				
15002	102.34	2.15				
20007	102.62	2.43				
24995	102.82	2.63				
27500	102.91	2.72				
30115	102.94	2.75				
32507	103.02	2.83				
35006	103.10	2.91				
37505	103.17	2.98				
40001	103.24	3.05				
42499	103.29	3.10				
45002	103.32	3.13				
47506	103.38	3.19				
49260			Cracked at clamping block			

Test #17

Strain Level: $\pm 3702\mu\varepsilon$

Mean Strain: $1019\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.89		-1163	-2349	5213	3781
1	99.91		-945	-2504	5023	3764
6			-442	-2798	4647	3723
7			-531	-2674	4763	3719
8			-460	-2707	4705	3706
9			-473	-2625	4735	3680
10	100.04		-425	-2663	4700	3682
100	100.34	0.30				
990	102.18	2.14				
2013	103.20	3.16				
2998	103.83	3.79				
3998	104.25	4.21	First crack observed			
4996	104.60	4.56				
5998	104.86	4.82				
7009	105.04	5.00				

Test #8

Strain Level: $\pm 2304\mu\varepsilon$

Mean Strain: $541\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.07		-300	-1670	2914	2292
1	100.08		-259	-1736	2884	2310
6			-200	-1752	2852	2317
7			-218	-1745	2866	2306
8			-172	-1756	2848	2302
9			-174	-1758	2846	2302
10	100.08		-163	-1760	2842	2301
100	100.18	0.10				
999	100.58	0.50				
2011	100.96	0.88				
3007	101.26	1.18				
3999	101.47	1.39				
4995	101.65	1.57				
6008	101.85	1.77				
7000	101.99	1.91				
7994	102.12	2.04				
9007	102.23	2.15				
10013	102.34	2.26				
15004	102.70	2.62				
20011	103.02	2.94				
25005	103.24	3.16				
27500	103.33	3.25				
29995	103.40	3.32	First crack observed			
32514	103.46	3.38				
34993	103.55	3.47				
37503	103.61	3.53				
40006	103.65	3.57				

Test #19

Strain Level: $\pm 2585\mu\varepsilon$

Mean Strain: $722\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.95		-805	-1687	3130	2409
1	99.99		-842	-1798	3376	2587
6			-688	-1878	3289	2584
7			-660	-1901	3263	2582
8			-685	-1863	3305	2584
9			-655	-1895	3283	2589
10	99.99		-674	-1861	3305	2584
100	100.10	0.11				
993	100.80	0.81				
1998	101.33	1.34				
2994	101.72	1.73				
4001	102.00	2.01				
4999	102.26	2.27				
6000	102.47	2.48				
6995	102.72	2.73				
7994	102.85	2.86				
9001	102.97	2.98				
9999	103.13	3.14				
12505	103.35	3.36				
15006	103.56	3.57	First crack observed			
17501	103.74	3.75				
20021	104.02	4.03				

Test #20

Strain Level: $\pm 2972\mu\varepsilon$

Mean Strain: $911\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.90		-583	-1915	4194	3055
1	99.96		-335	-2050	4002	3026
6			-167	-2010	3914	2962
7			-170	-2039	3921	2980
8			-120	-2069	3901	2985
9			-056	-2066	3879	2973
10	100.03		-052	-2050	3872	2961
100	100.25	0.22				
994	101.24	1.21				
1988	101.94	1.91				
2998	102.39	2.36				
3998	102.79	2.76				
4997	103.07	3.04				
5990	103.28	3.25				
6997	103.49	3.46				
8000	103.71	3.68				
9009	103.89	3.86				
9992	104.00	3.97				
10993	104.11	4.08	First crack observed			
12004	104.17	4.14				

Test #21

Strain Level: $\pm 2861\mu\varepsilon$

Mean Strain: $827\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.99		-493	-1952	4388	3170
1	100.05		-262	-2033	4194	3114
2	100.06		-109	-1983	3814	2899
6			027	-2015	3739	2877
7			059	-1993	3733	2863
8			059	-1974	3753	2864
9			096	-1977	3734	2856
10	100.11		167	-2019	3673	2846
100	100.27	0.16				
989	100.99	0.88				
1992	101.75	1.64				
3003	102.23	2.12				
3994	102.56	2.45				
4988	102.87	2.76				
6002	103.09	2.98				
6999	103.30	3.19				
8001	103.52	3.41				
9000	103.65	3.54				
10008	103.76	3.65				
11001	103.85	3.74				
11997	103.95	3.84	First crack observed			
13004	104.03	3.92				

Test #22

Strain Level: $\pm 2097\mu\varepsilon$

Mean Strain: $516\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.96		-625	-1473	2737	2105
1	99.97		-577	-1588	2677	2133
6			-535	-1570	2637	2104
7			-503	-1600	2592	2096
8			-529	-1566	2629	2098
9			-505	-1585	2602	2094
10	99.99		-502	-1578	2610	2094
100	100.03	0.04				
995	100.27	0.28				
2003	100.50	0.51				
3005	100.75	0.76				
3998	100.92	0.93				
4994	101.00	1.01				
5996	101.18	1.19				
7000	101.28	1.29				
7989	101.38	1.39				
8994	101.48	1.49				
9998	101.58	1.59				
12507	101.77	1.78				
15004	101.91	1.92				
17506	102.04	2.05				
20010	102.16	2.17				
22507	102.28	2.29				
25006	102.35	2.36	First crack observed			
26010	102.38	2.39				
27502	102.42	2.43				
30014	102.50	2.51				
32509	102.56	2.57				
35003	102.63	2.64				
37503	102.70	2.71				
40009	102.74	2.75				
42503	102.78	2.79				

Test #23

Strain Level: $\pm 2184\mu\varepsilon$

Mean Strain: $562\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.06		-135	-1557	2811	2184
1	100.11		010	-1588	2691	2140
6			100	-1591		
7			044	-1584	2812	2198
8			097	-1576	2755	2166
9			127	-1646	2733	2190
10			125	-1608	2741	2175
11	100.13		130	-1627	2751	2189
100	100.20	0.07				
999	100.59	0.46				
2007	100.87	0.74				
2996	101.21	1.08				
4001	101.45	1.32				
5007	101.62	1.49				
6002	101.81	1.68				
6998	101.92	1.79				
8002	102.05	1.93				
9001	102.14	2.01				
9994	102.30	2.17				
12507	102.53	2.40				
15006	102.74	2.61				
17502	102.88	2.75				
20011	103.00	2.87				
22512	103.08	2.95				
25009	103.21	3.08				
26014	103.23	3.10				
27495	103.30	3.17				
30013	103.39	3.26				
32500	103.46	3.33				
34995	103.51	3.38				
37500	103.50	3.45				
39999	103.65	3.52	First crack observed			

Test #24

Strain Level: $\pm 2262\mu\varepsilon$

Mean Strain: $513\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.12		-897	-1740	2989	2365
1	100.14		-712	-1736	2804	2270
6			-622	-1766	2751	2259
7			-622	-1743	2782	2263
8			-607	-1740	2780	2260
9			-592	-1746	2794	2267
10	100.15		-559	-1746	2771	2259
100	100.23	0.08				
998	100.68	0.53				
2001	101.30	1.15				
3008	101.45	1.30				
4001	101.71	1.56				
5004	101.88	1.73				
6004	102.04	1.89				
7007	102.24	2.09				
7998	102.38	2.23				
8998	102.50	2.35				
10003	102.61	2.46				
12510	102.76	2.61				
15006	103.02	2.87				
17511	103.24	3.09	First crack observed			

Test #25

Strain Level: ±3151με

Mean Strain: 1000με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.02		-1840	-1970	4550	3260
1	100.06		-1574	-2095	4353	3224
6			-1315	-2147	4178	3163
7			-1322	-2103	4279	3191
8			-1128	-2148	4112	3130
9			-1119	-2139	4143	3141
10	100.15		-1100	-2129	4129	3129
100	100.30	0.15				
1004	101.63	1.48				
2001	102.55	2.40				
2994	103.04	2.89				
4002	103.27	3.12				
4998	103.50	3.35				
5499	103.67	3.52				
5993	103.77	3.62				
6496	103.84	3.69				
6999	103.98	3.83	First crack observed			
6999	103.84					
7504	103.91	3.76				
8010	104.08	3.93				
8493	104.20	4.05				
9005	104.31	4.16				
9502	104.70	4.55				
9995	104.53	4.38				
10502	104.60	4.45				
11012	104.68	4.53				
12004	104.86	4.71				
12496	104.94	4.79				
13001	104.98	4.83				
13493	105.06	4.91	Crack observed on bottom surface			
14000	105.12	4.97				
14501	105.20	5.05				
15008	105.23	5.08				
15494	105.31	5.16				
15998	105.34	5.19				
16499	105.39	5.24				
17003	105.49	5.34				
17497	105.49	5.34				
18000	105.57	5.42				
18510	105.76	5.61				
18839	Gage failed					

Test #26

Strain Level: ±4026με

Mean Strain: 1412με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.95		-979	-2498	5830	4164
1	100.08		-700	-2512	5608	4060
6			-435	-2556	5574	4065
7			-272	-2603	5440	4022
8			-222	-2596	5422	4009
9			-183	-2590	5425	4008
10	100.14		-125	-2613	5437	4025
100	100.45	0.31				
999	102.72	2.58				
1560	103.41	3.27	First crack observed			
1560	103.19					
1998	103.50	3.26				
2498	104.16	4.02				
3002	104.63	4.49				
3505	104.97	4.83				
4006	105.23	5.09				
4506	105.46	5.32				
5005	105.69	5.55				
5521	105.94	5.80				
6009	106.14	6.00				
6500	106.24	6.10				
7012	106.27	6.13				
7506	106.42	6.28				
7998	106.50	6.36				
8521	Gage failed					

Test #27

Strain Level: ±3676με

Mean Strain: 1210με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.96		-904	-2412	5026	3719
1	100.00		-702	-2443	4904	3674
6			-491	-2462	4909	3686
7			-448	-2460	4890	3675
8			-390	-2469	4876	3673
9			-347	-2472	4877	3675
10	100.06		-334	-2463	4883	3673
100	100.40	0.34				
993	102.11	2.05				
1501	102.71	2.65				
1993	103.14	3.08				
2253	103.34	3.28				
2490	103.49	3.43				
2749	103.64	3.58	First crack observed			
2749	103.59					
3003	103.68	3.62				
3503	103.98	3.92				
4003	104.26	4.20				
4497	104.45	4.39				
4999	104.66	4.60				
5498	104.86	4.80				
6001	105.00	4.94				
6507	105.11	5.05				
7005	105.20	5.14				
7499	105.38	5.32	Crack observed on bottom surface			
7999	105.48	5.42				
8497	105.58	5.52				
9004	105.68	5.62				
9491	105.76	5.70				
9998	105.80	5.74				
10507	105.84	5.78				
10997	105.91	5.85				
11439	Gage failed					

Test #28

Strain Level: ±3361με

Mean Strain: 955με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.95		-1195	-2290	4347	3319
1	100.01		-958	-2380	4228	3304
6			-849	-2386	4351	3369
7			-770	-2404	4287	3346
8			-728	-2331	4281	3306
9			-775	-2370	4435	3403
10	100.09		-678	-2427	4336	3382
100	100.30	0.21				
1000	101.89	1.80				
1492	102.39	2.30				
1781	102.65	2.56				
1994	102.78	2.69				
2252	102.95	2.86				
2496	103.13	3.04				
2756	103.26	3.17				
3000	103.39	3.30				
3254	103.51	3.42	First crack observed			
3497	103.53	3.44				
3993	103.80	3.71				
4494	104.05	3.96				
5003	104.29	4.20				
5497	104.48	4.39				
6001	104.65	4.56				
6502	104.82	4.73				
6995	105.07	4.98	Crack observed on bottom surface			
7498	105.11	5.02				
7995	105.23	5.14				
8500	105.34	5.25				
8998	105.45	5.36				
9490	105.54	5.45				
10001	105.61	5.52				
10499	105.65	5.56				
11000	105.71	5.62				
11502	106.18	6.09				
11824	Gage failed					

Test #29

Strain Level: $\pm 3812\mu\varepsilon$

Mean Strain: $1225\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.93		-2549	-2570	5107	3839
1	99.95		-1797	-2555	5087	3821
6			-1483	-2591	5018	3805
7			-1426	-2604	5014	3809
8			-1403	-2595	5038	3817
9			-1380	-2553	5069	3811
10	100.02		-1291	-2591	5041	3816
100	100.38	0.36				
997	102.26	2.24				
1491	102.87	2.85	First crack observed			
1743	103.08	3.06				

Test #30

Strain Level: ±3292με

Mean Strain: 956με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.00		-2002	-2412	3995	3204
1	100.04		-3104	-2492	3923	3208
6			-2910	-2397	4167	3282
7			-2963	-2280	4412	3346
8			-2678	-2404	4158	3281
9			-200	-2342	4198	3270
10	100.10		-198	-2327	4239	3283
100	100.33	0.23				
999	102.03	1.93	First crack observed			
999	102.00					
1246	102.31	2.21				
1503	102.58	2.48				
1757	102.87	2.77				
2002	103.11	3.01				
2254	103.29	3.19				
2499	103.47	3.37				
2752	103.62	3.52				
2999	103.78	3.68				
3250	103.90	3.80				
3504	104.03	3.93				
3787	104.16	4.06				
3998	104.26	4.16				
4501	104.34	4.24				
4996	104.49	4.39				
5504	104.68	4.58				
6001	104.78	4.68				
6505	104.88	4.78				
7006	105.02	4.92	Crack observed on bottom surface			
7493	105.18	5.08				
7997	105.28	5.18				
8516	105.40	5.30				
9011	105.50	5.40				
9503	105.58	5.48				
9996	105.64	5.54				
10498	105.64	5.54				
11019	106.42	6.32				
11284	Gage failed					

Test #31

Strain Level: $\pm 3908\mu\varepsilon$

Mean Strain: $1146\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
1	99.92		-982	-2800	4980	3890
2	99.92		-967	-2785	4994	3890
6			-829	-2770	5042	3906
7			-776	-2788	5016	3902
8			-763	-2759	5051	3905
9			-727	-2755	5044	3900
10	99.97		-689	-2779	5071	3925
100	100.35	0.38				
495	101.47	1.50				
593	101.67	1.70				
694	101.84	1.87				
806	102.00	2.03	First crack observed			
1007	102.26	2.29				
1249	102.58	2.61				
1501	102.86	2.89				
1748	103.03	3.06				
1990	103.33	3.36				
2248	103.53	3.56				
2496	103.70	3.73				
2759	103.90	3.93				
2997	104.04	4.07				
3258	104.15	4.18				
3495	104.2[illegible]	4.29				
3746	104.37	4.40				
3998	104.47	4.50				
4249	104.55	4.58				
4495	104.66	4.69				
4754	104.75	4.78				
4999	104.88	4.91				
5253	104.93	4.96				
5502	105.02	5.05				
5747	105.10	5.13				
6002	105.17	5.20				
6254	105.22	5.25				
6504	105.28	5.31				
6749	105.35	5.38				
6999	105.35	5.38				
7111	105.41	5.44				
7207	105.45	5.48				
7301	105.47	5.50				
7402	105.50	5.53				
7497	105.50	5.53				

Test #31 (Continued)

Cycles	R_g	Δ	
7604	105.51	5.34	
7702	105.56	5.59	
7796	105.56	5.59	
7901	105.58	5.61	
8001	105.60	5.63	
8100	105.62	5.65	
8208	105.66	5.69	
8304	105.66	5.69	
8396	105.69	5.72	
8495	105.70	5.73	
8600	105.70	5.74	
8702	105.71	5.74	
8807	105.80	5.83	
8902	105.76	5.79	
9001	105.79	5.82	
9095	105.75	5.78	
9150	105.71	5.74	Hand cycled for remainder of test
9250	105.72	5.75	
9275	105.72	5.75	
9300	105.72	5.75	
9325	105.72	5.75	
9350	105.74	5.77	
9375	105.74	5.77	
9400	105.74	5.77	
9425	105.73	5.76	
9450	105.70	5.73	
9475	105.70	5.73	
9500	105.70	5.73	
9525	105.70	5.73	
9550	105.72	5.75	
9575	105.72	5.75	
9600	105.75	5.78	
9625	105.75	5.78	
9650	105.77	5.80	
9675	105.77	5.80	
9700	105.77	5.80	
9725	105.79	5.82	
9750	105.83	5.86	
9775	105.83	5.86	
9800	105.83	5.86	
9825	105.93	5.96	
9850	105.98	6.01	
9875	106.01	6.04	
9900	106.13	6.16	
9925	106.16	6.19	
9950	106.27	6.30	
9975	106.36	6.39	
10000	106.46	6.49	

Test #31 (Continued)

Cycles	R_g	ΔR
10025	106.60	6.63
10050	106.65	6.68
10075	106.81	6.84
10100	106.96	6.99
10125	107.27	7.30
10135	Gage failed	

Test #32

Strain Level: ±1677με

Mean Strain: 248με

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.11		307	-1412	2019	1716
1	100.16		355	-1327	1967	1647
6			402	-1427	1938	1683
7			407	-1419	1927	1673
8			411	-1426	1932	1679
9			416	-1423	1926	1675
10	100.20		423	-1428	1924	1676
100	100.22	0.02				
1006	100.35	0.15				
2007	100.43	0.23				
3001	100.53	0.33				
3999	100.63	0.43				
4997	100.71	0.51				
5998	100.80	0.60				
7001	100.85	0.65				
7999	100.90	0.70				
8999	100.97	0.77				
9994	101.04	0.84				
12502	101.17	0.97	First crack observed			
14998	101.23	1.03				
17503	101.31	1.11				
20000	101.39	1.19				
22500	101.48	1.28				
24998	101.56	1.36				
27500	101.61	1.41				
30006	101.65	1.45				
32495	101.73	1.53				
34999	101.79	1.59				
37503	101.84	1.64				
39998	101.88	1.68				
44999	101.97	1.77				
50002	102.03	1.83				
54996	102.10	1.90				
60005	102.14	1.94				
65009	102.20	2.00				
70008	102.29	2.09				
75006	102.33	2.13				
80002	102.39	2.19				
85003	102.44	2.24				
90005	102.51	2.31				
95008	102.53	2.33				
100007	102.58	2.38				
110006	102.64	2.44				

Test #32 (Continued)

Cycles	R_g	ΔR	
120000	102.70	2.50	
130006	102.76	2.56	
140005	102.82	2.62	
150014	102.87	2.65	
160010	102.91	2.71	
169997	102.93	2.73	
180013	103.00	2.80	
190006	103.04	2.84	
200008	103.09	2.89	
210008	103.11	2.91	
220007	103.14	2.94	
230011	103.17	2.97	
239999	103.19	2.99	
250003	103.22	3.02	
260002	103.25	3.05	
269997	103.27	3.07	
279987	103.28	3.08	
290000	103.34	3.14	
295010	103.39	3.19	
305008	103.38	3.18	
309994	103.38	3.18	
315132	103.40	3.20	
319995	103.43	3.23	
324996	103.45	3.25	
329997	103.51	3.31	
334001	103.59	3.39	Epoxy backing of gage penetrated
334991	103.60	3.40	
337488	103.67	3.47	
338352	103.73	3.53	
338835	103.76	3.56	
339519	103.79	3.59	
340874	104.13	3.93	
341608	Gage failed		

Test #33

Strain Level: $\pm 1929\mu\varepsilon$

Mean Strain: $294\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.14		256	-1612	2364	1988
1	100.19		363	-1634	2253	1944
6			412	-1625	2230	1928
7			423	-1631	2227	1929
8			432	-1635	2236	1936
9			449	-1637	2213	1925
10	100.19		450	-1635	2222	1929
100	100.23	0.04				
489	100.37	0.18				
996	100.47	0.28				
1499	100.62	0.43				
1998	100.76	0.57				
2994	100.97	0.78	First crack observed			
4004	101.12	0.93				
5004	101.25	1.06				
5998	101.40	1.21				
6996	101.51	1.32				
7987	101.63	1.44				
9002	101.78	1.59				
9996	101.84	1.65				
12497	102.06	1.87				
14998	102.25	2.06				
17495	102.40	2.21				
19994	102.53	2.34				
22495	102.64	2.45				
24995	102.76	2.57				
27505	102.86	2.67				
30005	102.94	2.75				
32498	103.03	2.84				
34998	103.10	2.91				
37511	103.18	2.99				
39994	103.25	3.06				
42500	103.30	3.11				
44991	103.35	3.16				
47498	103.42	3.23				
49998	103.46	3.27				
52500	103.50	3.31				
55005	103.57	3.38				
57502	103.62	3.43				
59997	103.69	3.50				
62496	103.72	3.53				
65004	103.77	3.58				

Test #33 (Continued)

Cycles	R_g	ΔR	
67508	103.81	3.62	
70007	103.84	3.65	
72500	103.87	3.68	
75003	103.90	3.71	
77493	103.94	3.75	
80004	103.96	3.77	
82499	104.00	3.81	
85009	104.03	3.84	
87503	104.05	3.86	
90004	104.09	3.90	
92498	104.11	3.92	
94996	104.11	3.92	
97499	104.16	3.97	
100004	104.19	4.00	
102494	104.23	4.04	
105001	104.26	4.07	
107500	104.31	4.12	
109995	104.37	4.18	
112496	104.41	4.22	
114986	104.45	4.26	
117494	104.46	4.27	Crack observed on bottom surface
119998	104.49	4.30	
122496	104.51	4.32	
124999	104.55	4.36	
127497	104.60	4.41	
128992	104.64	4.45	
130005	104.73	4.54	
130494	104.79	4.60	
130996	104.90	4.71	
131272	105.00	4.81	
131569	105.14	4.95	
131731	105.27	5.08	
132083	105.86	5.67	
132301	Gage failed		

Test #34

Strain Level: $\pm 2450\mu\varepsilon$

Mean Strain: $502\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.90		-1092	-1950	2955	2453
1	99.94		-900	-1962	2938	2450
6			-815	-1963	2920	2442
7			-825	-1950	2950	2450
8			-808	-1954	2946	2450
9			-782	-1973	2917	2445
10	99.96		-782	-1960	2964	2462
100	100.06	0.10				
512	100.52	0.56				
998	100.90	0.94				
1496	101.16	1.20				
1995	101.42	1.46	First crack observed			
3002	101.92	1.96				
4001	102.28	2.32				
5002	102.53	2.57				
6001	102.82	2.86				
6999	102.99	3.03				
7996	103.03	3.07				
8996	103.16	3.20				
10003	103.29	3.34				
12495	103.60	3.64				
15005	103.82	3.86				
17499	104.03	4.07				
20005	104.17	4.21				
22509	104.39	4.43				
25011	104.46	4.50				
27509	104.52	4.56				
29998	104.61	4.65	Crack observed on bottom surface			
32502	104.72	4.76				
35004	104.77	4.81				
37498	104.84	4.88				
38370	104.88	4.92				
39000	105.04	5.08				
39483	105.39	5.43				
39733	105.76	5.80				
39885	106.10	6.14				
40136	Gage failed					

Test #35

Strain Level: $\pm 3219\mu\varepsilon$

Mean Strain: $925\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	100.12		252	-2250	4366	3308
1	100.19		397	-2295	4225	3260
6			600	-2283	4151	3217
7			614	-2280	4149	3215
8			639	-2268	4149	3209
9			695	-2295	4163	3229
10	100.28		750	-2300	4150	3225
100	100.51	0.23				
499	101.13	0.85				
990	101.69	1.41				
1493	102.14	1.86				
1996	102.51	2.23	First crack obserbed			
3002	103.06	2.78				
4007	103.54	3.26				
4992	103.81	3.53				
5996	104.07	3.79				
6995	104.30	4.02				
7994	104.48	4.20				
9004	104.63	4.35				
9998	104.76	4.48				
10999	104.88	4.60				
12000	104.95	4.67				
12997	105.06	4.78				
14002	105.15	4.87				
15003	105.26	4.98				
16038	105.35	5.07				
16999	105.42	5.14				
17998	105.48	5.20				
18992	105.53	5.25				
19992	105.58	5.30				
21000	105.60	5.32				
21644	105.60	5.32				
21994	105.71	5.43				
22207	105.94	5.66				
22282	106.07	5.79				
22383	106.35	6.07				
22505	106.72	6.44				
22573	107.04	6.76				
22606	107.35	7.07				
22621	Gage failed					

Test #36

Strain Level: $\pm 2444\mu\varepsilon$

Mean Strain: $623\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R
0	99.98		-620	-1755	3495	2625
1	100.01		-372	-1790	3260	2525
6			-189	-1774	3124	2449
7			-165	-1792	3097	2445
8			-155	-1777	3118	2448
9			-138	-1772	3101	2437
10	100.08		-080	-1820	3065	2443
100	100.18	0.10				
502	100.50	0.42				
1017	100.74	0.66				
1500	101.01	0.93				
1998	101.17	1.09	First crack observed			
3000	101.53	1.45				
3999	101.77	1.69				
5005	102.00	1.92				
5997	102.20	2.12				
7002	102.35	2.27				
8000	102.50	2.42				
9003	102.61	2.53				
10006	102.72	2.64				
12507	102.99	2.91				
15007	103.17	3.09	Crack observed on bottom surface			
17508	103.35	3.27				
20013	103.51	3.43				
22497	103.61	3.53				
24997	103.76	3.68				
27500	103.86	3.78				
30004	103.92	3.84				
31004	103.97	3.89				
32001	104.00	3.92				
32993	104.02	3.94				
34008	104.07	3.99				
35004	104.11	4.03				
35996	104.12	4.04				
37509	104.16	4.08				
40002	104.21	4.13				
42505	104.27	4.19				
45010	104.33	4.25				
47508	104.37	4.29				
49995	104.42	4.34				
52508	104.48	4.40				
55008	104.52	4.44				

Test #36 (Continued)

Cycles	R_g	Δ
57497	104.54	4.46
60002	104.58	4.50
62502	104.62	4.54
64999	104.68	4.60
67503	104.71	4.63
70005	104.75	4.67
72507	104.78	4.70
74986	104.86	4.78
76000	104.90	4.82
76507	104.95	4.87
77013	105.02	4.94
77992	105.16	5.08
78507	105.36	5.28
79006	105.57	5.49
79503	Gage failed	

Test #37

Strain Level: $\pm 4316 \mu\varepsilon$

Mean Strain: $1458 \mu\varepsilon$

Cycles	R_g	Unstrained	ε_n	ε_c	ε_t	ε_R
0	99.94	-4263	-4700	-7558	1073	4316

Test #38

Strain Level: $\pm 4160\mu\varepsilon$

Mean Strain: $1453\mu\varepsilon$

Cycles	R_g	Unstrained	ε_n	ε_c	ε_t	ε_R
0	100.01	-4375	-5028	-7735	584	4160

Test #1A

Strain Level: $\pm 3826\mu\varepsilon$

Mean Strain: $1236\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R	
0	100.02		-195	-2513	5149	3831	
1	100.03		-155	-2593	5128	3861	
6			072	-2584	5069	3827	
7			088	-2569	5083	3826	
8			146	-2605	5054	3830	
9			178	-2595	5053	3824	
10	100.10		214	-2585	5057	3821	2/3/70
10	100.91						2/17/70
100	101.14						
1005	103.07	***					
1005	102.35						2/18/70
1005	102.29						5/14/70

*** Readings taken on 2/17/70 did not register the expected results. At that time no explanation was available. However, after checking the set-up it was felt that possibly a partial ground existed in the terminal strip. Accordingly a new terminal strip was mounted 2/18/70 and the resistance change checked. The results of this check and following tests seemed to verify this idea.

Test #2A

Strain Level: $\pm 3958\mu\varepsilon$

Mean Strain: $1256\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R	
0	100.14		423	-2635	5330	3983	
1	100.18						
6			668	-2638	5289	3964	
7			751	-2670	5249	3960	
8			787	-2674	5241	3958	
9			823	-2673	5239	3956	
10	100.29		898	-2695	5207	3951	2/3/70
10	100.20						
100	100.62						2/18/70
100	100.55						5/14/70

Test #3A

Strain Level: $\pm 4389\mu\varepsilon$

Mean Strain: $1420\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R	
0	99.94		-623	-2877	6093	4485	
1	99.99		-527	-2955	6017	4486	
6			-150	-2962	5861	4412	
7			-107	-2951	5841	4396	
8			-040	-2957	5808	4383	
9			022	-2969	5793	4381	
10	100.12		053	-2952	5792	4372	2/3/70
10	100.10		-1350	-3022	5739	4380	
100	100.61	0.51					
1002	103.03	2.91					
1253	103.39	3.27					4/1/70
1523	103.71	3.61					
1991	104.25	4.15					
2499	104.68	4.58					
2996	105.02	4.92					
3498	105.27	5.17					
3998	105.50	5.40					
4490	105.74	5.64					
5002	105.87	5.77					
5554	106.08	5.98	Crack observed on bottom sruface				
6111	106.18	6.08					
6242	106.23	6.13					
6497	106.28	6.18					
6998	106.34	6.24					
7207	106.77	6.67					
7312	Gage failed						4/15/70

Test #4A

Strain Level: $\pm 3980\mu\varepsilon$

Mean Strain: $1126\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R	
0	100.09		090	-2703	5090	3897	
1	100.15		221	-2771	5030	3901	
6			422	-2800	5146	3973	
7			402	-2745	5228	3987	
8			512	-2814	5147	3981	
9			555	-2833	5174	3953	
10	100.21		649	-2881	5132	4007	2/3/70
10	100.19		-858	-2907	5116	4010	
100	100.62						4/1/70
100	100.57						5/14/70

Test #5A

Strain Level: $\pm 2637\mu\varepsilon$

Mean Strain: $1334\mu\varepsilon$

Cycles	R_g	ΔR	ε_n	ε_c	ε_t	ε_R	
0	99.93		-889	-2616	5344	3980	
1	99.93		-769	-2665	5318	3992	
6			-540	-2663	5263	3963	
7			-509	-2640	5277	3960	
8			-436	-2673	5248	3961	
9			-413	-2669	5245	3958	
10	100.02		-395	-2662	5329	3996	2/3/70
10	99.98		-488	-1982	3663	2822	
11			-017	-2075	3210	2643	
12			012	-2059	3198	2649	
13			007	-2047	3206	2627	
14			-008	-2034	3232	2633	
15	100.05	0.07	023	-2052	3217	2635	
100	100.20	0.22					
1009	100.94	0.96					
1992	101.52	1.54					
3000	101.93	1.95					
4002	102.27	2.29					
4992	102.52	2.54					
6002	102.73	2.75					
6988	102.94	2.96					
7999	103.13	3.15					
8994	103.24	3.26					
10003	103.41	3.43					
12499	103.68	3.70	First crack observed				
15006	103.92	3.94					3/10/70

APPENDIX E

MEAN STRAIN

A remark is in order concerning the significance of the quantity which has been called mean strain in this thesis. Through oversight, no strain indication was observed when the specimen was in an unstrained condition. Accordingly, there is no basis for determining a reference strain indication which is necessary to determine actual strain levels at any time, and in particular to determine the mean strain. However, it was observed that the strain indication always was positive when the specimen was in the position causing greatest tensile strain, and that the loading on the specimen was actually such as to cause tensile strain in this position. Similarly, when the loading was such as to cause maximum compressive strain, the strain actually was compressive and the strain indication was negative. Accordingly, it may be concluded that the mean strain did not exceed the strain level (ε_R) in absolute value.

In Appendix A there is discussion of other tests made with varying mean strains. These tests indicate that the variations in mean strain do not appear to have a pronounced effect upon the performance of the gage. Furthermore, from a qualitative examination of the eccentric mechanism on the fatigue machine, it appears that when the specimen is in the neutral position, the actual strain level is quite small compared to the strain amplitude due to cycling.

In order to shed definite light on this matter, two final experiments were conducted in which a strain indication was

observed for the specimen in an unstrained condition. The results are:

	Test Number 37	Test Number 38
ε_R	4316	4160
Mean Strain (As recorded in this study)	1458	1453
True Mean Strain	1021	800

This indicates that the true mean strain is about 500$\mu\varepsilon$ less than the quantity herein called mean strain when the specimen was positioned so as to give an ε_R of about 4200$\mu\varepsilon$. Presumably the descrepancy is of the same order of magnitude when the specimen is loaded in other positions.

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13. ABSTRACT

Recent tests by G. L. Rowe indicated the possibility of monitoring faitgue damage of 70-30 copper-nickel by use of a commercial fatigue life gage. The work reported herein, however, which includes tests at cyclic strain levels considerably higher and lower than those used by Rowe, suggests that much more study and development will be required before in-service monitoring will be useful or reliable. Fatigue failure, using initial surface crack formation as a criterion, takes place at low cyclic strain levels with appreciably smaller gage indication than does failure at medium or high cyclic strain levels. It is further noted that ability to detect surface cracks depends greatly upon the expertise of the observer so that a less subjective criterion of failure should be developed.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fatigue						
70-30 Copper-Nickel						
S/N Fatigue Life Gage						

el.

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